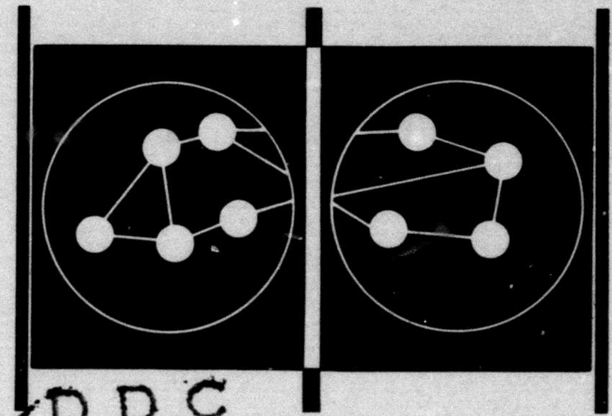
Economic Analysis of Integrated DOD Voice and Data Networks

Final Report



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NETWORK ANALYSIS CORPORATION

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(6) ECONOMIC ANALYSIS OF INTEGRATED DOD VOICE AND DATA NETWORKS.

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ECONOMIC ANALYSIS OF INTEGRATED DOD VOICE AND DATA NETWORKS

EXECUTIVE SUMMARY

I. OBJECTIVE AND MAJOR CONCLUSION

The objective of this study is to evaluate alternative switching strategies for future integrated DOD voice and data networks. Three fundamental problems are addressed:

- The economics of integrating voice and data applications in a common communications system.
- The comparison of alternative switching technologies for integrated voice and data networks.
- The cost-effectiveness of alternative voice digitization rates and strategies.

The major conclusion of this study is that the packet-switching technology is substantially more cost-effective for serving DOD voice and data requirements than the other alternatives examined. This conclusion holds whether voice and data are carried by separate networks or by one integrated network. Potential monthly cost savings range from $1 million to more than $70 million depending on the volume of data carried and the voice digitization rate employed.

Results of studies regarding future DOD communications are provided and the sensitivity of the results are tested with respect to traffic variations, cost trends of switching and transmission, and network performance variables. The significant variables which affect the results are identified and quantified.

The intent of this study is to identify and quantify network technologies which demonstrate long-term low operating costs. This is a necessary effort to provide the basis for determining the most cost-effective evolutionary path for DOD communications. It is

recognized that transition problems and associated costs may be other important factors determining the ultimate evolutionary path. However, determining these costs was not an objective of this study. Nevertheless, this study provides a framework and a target technology for detailed evolution planning and cost analysis.

II. SYSTEM OPTIONS CONSIDERED

Three broad switching technologies and variations thereof are investigated and compared. The switching technologies are: circuit switching, packet switching, and hybrid (circuit-packet) switching. Each switching technology can accommodate either voice or data applications separately or combined voice and data requirements in an integrated fashion. The switching alternatives compared are defined below:

CIRCUIT-SWITCHING OPTIONS:

Advanced circuit-switching technology utilizing CCIS (Common Channel Interoffice Signaling) for circuit setup and disconnection is considered.

Traditional Circuit Switching:

An end-to-end circuit is established for a pair of voice or data users. The end-to-end transmission facilities are dedicated to users for the duration of use. The circuit is disconnected when either party hangs up.

Fast Circuit Switching:

Voice and bulk data applications use the traditional circuit-switching concept. For interactive data users, a circuit is established for every message when ready to be sent and then disconnected after transmission. Specifically, the circuit is not dedicated to the user during his idle "think time" period; however the channel capacity not used during circuit setup and disconnection is taken into account. This concept assumes advanced digital switches enabling the set up of a circuit in 140 msec so that delay requirements for interactive data applications can be satisfied. It is likely that this technology will be available to the DOD in the timeframe contemplated by this study.

Ideal Circuit Switching:

This scenario is almost the same as fast circuit switching except that circuit setup and disconnection are assumed to occur in zero time. Hence no channel capacity is wasted during setup and disconnection. While ideal circuit switching is not physically realizable, it is considered in order to obtain a lower bound on transmission cost for the circuit-switching technology.

HYBRID-SWITCHING OPTIONS:

Switching and transmission facilities are dynamically shared between traffic using both circuit-switched and packet-switched modes. Voice is accommodated by the circuit-switched mode, interactive data applications are accommodated by the packet-switched mode, and bulk data applications may use either the circuit-switched or packet-switched modes depending on the operating discipline selected. Two options for sharing of transmission capacity are examined.

Fixed Boundary Frame Management:

The partition of link capacity between circuit-switched and packet-switched traffic is fixed.

Moveable Boundary Frame Management:

While a boundary is assigned between the packet and circuit transmission capacities, packet-switched traffic can dynamically utilize idle channel capacity assigned to the circuit-switched mode.

The hybrid-switching technology was considered in order to provide circuit switching for voice and packet switching for data applications. This technology also provides a potential transition technology to an integrated voice and data packet-switching system. A detailed investigation of the moveable boundary strategy was necessary because the savings in transmission cost that would result by using the moveable boundary strategy could not have been estimated *a priori*.

PACKET-SWITCHING OPTIONS:

Under these options both voice and data are accommodated by the store-and-forward packet-switched concept. However different packet sizes and different transport protocols are used for data and speech. The packet voice protocol options considered are:

Fixed Path Protocol (FPP):

When a voice call originates, a signaling message is propagated to the destination to set up a path for the call. The path setup involves setting appropriate pointers at tandem switching nodes which determine the outgoing link for every input voice packet. No channel capacity is reserved or switch capacity dedicated. Voice packets follow the fixed path. When either party hangs up, the path is released.

Path Independent Protocol (PIP):

In this protocol, no path is set up. Each voice packet is transported to the destination independently of other packets of the same conversation. Packets can use alternate routes as appropriate.

III. ASSUMPTIONS AND DISCUSSION

Assumptions include voice and data traffic volumes to be accommodated, the voice digitization rate of active voice sources, switching and transmission cost components, and network performance requirements.

THE DATA BASE

The traffic data base used is derived from the present DOD voice traffic on the AUTOVON voice system and a scaled DOD data traffic projected for the AUTODIN II data network. Only the projected traffic volume of AUTODIN II is varied whereas the traffic pattern is assumed unchanged. Voice traffic intensity is measured in Erlangs (E) whereas

data traffic is measured in Megabits per second (Mbps). The average voice load in Erlangs is computed by multiplying the average call origination rate by the average holding time per call. An average load in Erlangs is equivalent to the average number of circuits that will be occupied by voice subscribers. The throughput requirements of the voice traffic in bits per second depends on the voice digitization rate with which the analog voice waveform is converted to digital form.

The nominal traffic requirements are 2,700 Erlangs (E) AUTOVON voice traffic, and 36.15 Mbps scaled AUTODIN II data traffic. Data traffic is assumed to be composed of bulk data transfer applications and interactive applications. The nominal volume composition assumes 50% bulk and 50% interactive but is varied over a wide range for sensitivity analysis. In addition to the nominal data traffic of 36.15 Mbps, system costs are obtained for data throughputs of 11.6 Mbps, 86.8 Mbps, and 202.4 Mbps. Moreover, cost and performance for voice load requirements of 675 Erlangs and 1,350 Erlangs (25% and 50% of the AUTOVON load) are also investigated. The voice digitization rate considered is varied from 2.4 Kbps to 64 Kbps for an active speech source. The combination of variation of traffic and voice digitization rate results in consideration of digital traffic ranging from 3% voice and 97% data to 94% voice and 6% data.

COST MODELS

Transmission:

Cost factors are based on current procurement estimates for tariffed communication lines and hardware. Communication line costs include mileage and termination charges and are calculated for the backbone network communication lines. The current AT&T Digital Data Service (DDS) tariffs are used in the study.

Switching:

Cost factors include purchase price, installation, initial support, operations, maintenance, and amortization. Cost factors not considered are network management costs, the security costs of specially cleared switches, operational personnel, and the cost of encryption devices.

The following components are taken into account in computing processing capacity, memory size, and switching cost. Processing components include: Operating System Overhead, Circuit-Switching Rate, Data Packet-Switching Rate, Voice Packet-Switching Rate, Total Character Transfer Rate, and Hybrid Switch Complexity (Frame Rate, Circuit and Packet Rates per Frame, Moving Boundary Complexity). Memory components include: Memory Overhead, Storage for Tables (Circuit and Packet Routing Tables, Calls in Progress Tables), and Storage for Store-and-Forward Data.

The switch cost model corresponds to current costs of computer systems. The cost of switching nodes is a function of processing capacity requirements, storage requirements, and the cost of channel interfaces. Switch complexity is taken into account and expressed in the processing capacity. Typically, for the same throughput requirements, a hybrid switch is the most costly and a circuit switch the least costly switch. Purchase price per switching node ranges from \$1.8 million to \$27 million depending on the voice digitization rate, the switching technology, and the amount of data and voice traffic to be accommodated. Note that because of the small number of switches used in comparison to AUTOVON, each switching node must have substantially higher throughput than the AUTOVON switches. In addition these switches must process 25 times the data traffic projected for the initial AUTODIN II system. The highest switch costs are obtained at voice digitization rate of 64 Kbps (PCM rate). The cost of low bit rate VDR devices is parametrized in the study.

Apart from current switching and transmission costs, the sensitivity of network cost to component hardware and transmission costs is derived using two cost scenarios:

1. Switching Cost - 10% of current
   Transmission Cost - current.

2. Switching Cost - current
   Transmission Cost - 10% of current.

It is noted that in the hybrid switch case, no attempt is made to use speech compression techniques that may become available for such systems. Further studies to examine such options are currently being considered.

<u>Conversion Factor:</u> The switch and digitization device costs are given in purchase price and are converted to monthly cost using cost procedures utilized by the Defense Communications Agency (DCA). The conversion factor is based on a 10-year amortization

plan; it includes installation charge at 20% base cost, initial support charge at 67% base cost, and a 10-year operation and maintenance cost at 47% base cost. It assumes a redundancy factor of 1.5 for equipment, a capital factor of about 5% per year, based on 10% annual interest over ten years. Using the above analysis results in a Conversion Factor of 0.0438 from Purchase Price to Monthly Cost.

NETWORK PERFORMANCE

In the circuit and hybrid-switching technologies, voice calls are engineered on a blocking basis and data subscribers on a delay basis. Blocking implies that a certain percentage of voice calls will be rejected by the system via a busy tone because of unavailability of facilities. Data subscribers under the circuit-switching technology are assumed to automatically redial every 10 msec when blocked, until an end-to-end circuit is established. The packet-switching network is engineered on a delay basis for voice and data subscribers.

All networks are engineered for nominal:

1% end-to-end blocking for circuit-switched voice
200 msec end-to-end packet delay for interactive data users and packet voice
600 msec end-to-end packet delay for bulk data applications.

The percentage of blocked calls for which the networks are engineered is varied from 0.4% to 10%, and the end-to-end packet delay is varied from 200 msec to 1 sec; the corresponding network cost is calculated to determine the effect of performance requirement variations. Several cases where an average backbone voice packet delay is constrained to 50 msec are also examined.

LOCATION OF VOICE DIGITIZATION DEVICES

Investigations are performed under one of the following assumptions:

1. Voice requirements occur in the backbone network in digital form at the bit rate indicated. The location and cost of the digitization process is not considered.

2. Voice is digitized at the origination backbone node.

3. Voice is digitized at subscriber handsets.

The absolute backbone network cost differences between alternative network technologies are independent of the location of the digitization process, and are not affected by the location of the voice digitizers. Under Assumption (2) low bit rate digitizers are provided in the backbone network with the objective of reducing total system cost. This case is applicable for public voice and data systems or for DOD subscribers who do not require end-to-end encryption. An integrated DOD system may consist of some subscribers with digitizers at the handset and other subscribers whose voice signals are digitized in the backbone network. Assumption (3) relates to the case where all DOD subscriber handsets include voice digitizers. In this case, while total cost of digitizers would increase because of the larger number of units required, savings would be generated by reducing the cost of local access. Those savings were not investigated but are expected to be greatest under the packet-switching technology because of its inherent multiplexing capability.

NETWORK STRUCTURE

The investigation and comparison of switching technologies is developed for backbone networks with backbone switching nodes at the eight AUTODIN I switch locations. The backbone voice traffic corresponding to these locations is determined by assigning the current AUTOVON switch traffic requirements to the eight backbone nodes according to the nearest distance criterion. Network links and their capacities are obtained by automated network design techniques using the minimum cost criterion subject to satisfying network performance requirements. However, a two-connectivity (each node connected to at least two other nodes) requirement is imposed to guarantee network reliability.

The number of backbone nodes is held constant in the present investigations since previous studies conducted by Network Analysis Corporation have shown that the optimum number of backbone nodes for comparable throughput levels ranged from five to twelve, and that the cost differences in this range are insignificant. Moreover, well-designed networks with as many as 30 distributed switches have been shown by NAC to lead to networks with communication and hardware costs only a few percent above the minimum. Thus, the number of backbone nodes is not a critical issue from a communications efficiency

perspective and this number can be determined based on other criteria such as security and survivability.

Detailed design of the local distribution networks is not addressed in this study. However, preliminary analyses of local distribution network technologies result in the expectation that the relative ranking of switching technologies identified in this report will be preserved. This expectation derives from the following points. For voice digitization at the backbone nodes, local access lines would be similar under the circuit, packet or hybrid technologies. Furthermore, if voice digitization occurs at the handset (or at a local building telephone branch exchange), the circuit-switching technology should lead to equal or greater local access line costs than the packet-switching technology. Cost would be equal if digitization occurs at high data rates since an equal number of access lines would be required for either technology. At low digitization rates, the natural multiplexing capabilities of packet switching would tend to increase the effective utilization of the local access lines and hence decrease the number and cost of the lines required. Previous studies conducted by Network Analysis Corporation have shown that the cost of local distribution networks can be on the order of 50% or more of the total system line cost. Hence, local access cost is a substantive element which deserves further study, in particular when issues such as the proper number of backbone nodes for survivability constraints is also examined. It is planned to examine this issue in more detail in the near future.

IV. CONCLUSIONS

The major conclusions of the investigations are summarized below and illustrated in Figures 1 - 3:

- *On the basis of total backbone network cost (lines and switching) for the specific data bases and requirements that were studied and the cost models assumed, the ranking of switching technologies in increasing cost for integrated voice and data is: packet switching, hybrid (circuit-packet) switching, ideal circuit switching, fast circuit switching, traditional circuit switching (Figure 1).*

- *The ranking of switching technologies remains virtually unchanged under a variety of traffic, cost, and parameter assumptions, with packet switching providing the lowest cost networks for all cases studied. This conclusion is*

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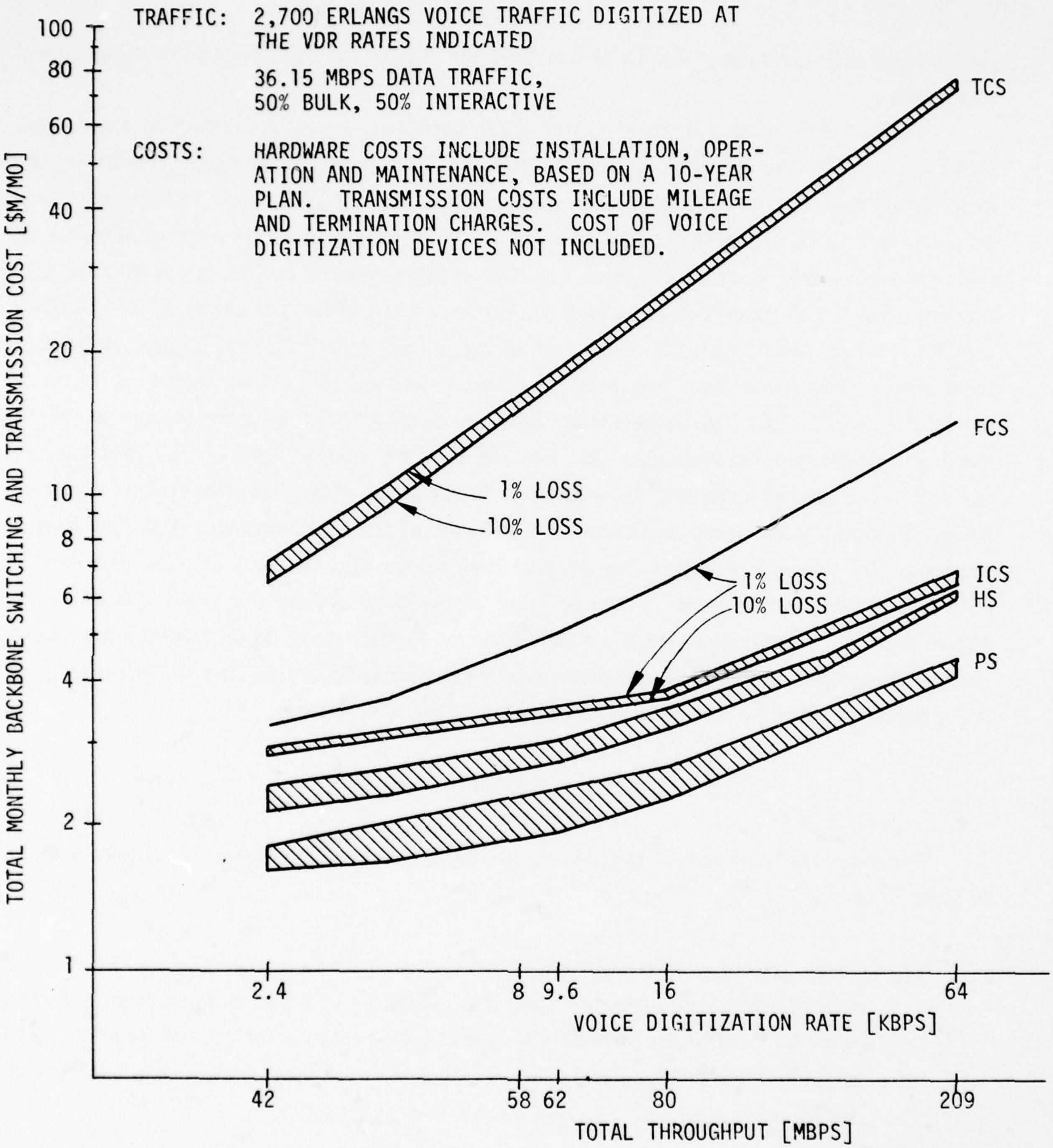


MONTHLY BACKBONE SWITCHING AND TRANSMISSION COST AS A FUNCTION OF VOICE DIGITIZATION RATE (VDR) AND SWITCHING TECHNOLOGY (TCS - TRADITIONAL CIRCUIT SWITCHING; FCS - FAST CIRCUIT SWITCHING; ICS - IDEAL CIRCUIT SWITCHING; HS - HYBRID SWITCHING; PS - PACKET SWITCHING). COST RANGES INDICATE ALTERNATIVE OPERATION SCENARIOS (HS AND PS) OR BLOCKING PROBABILITY RANGE (TCS, ICS).

FIGURE 1

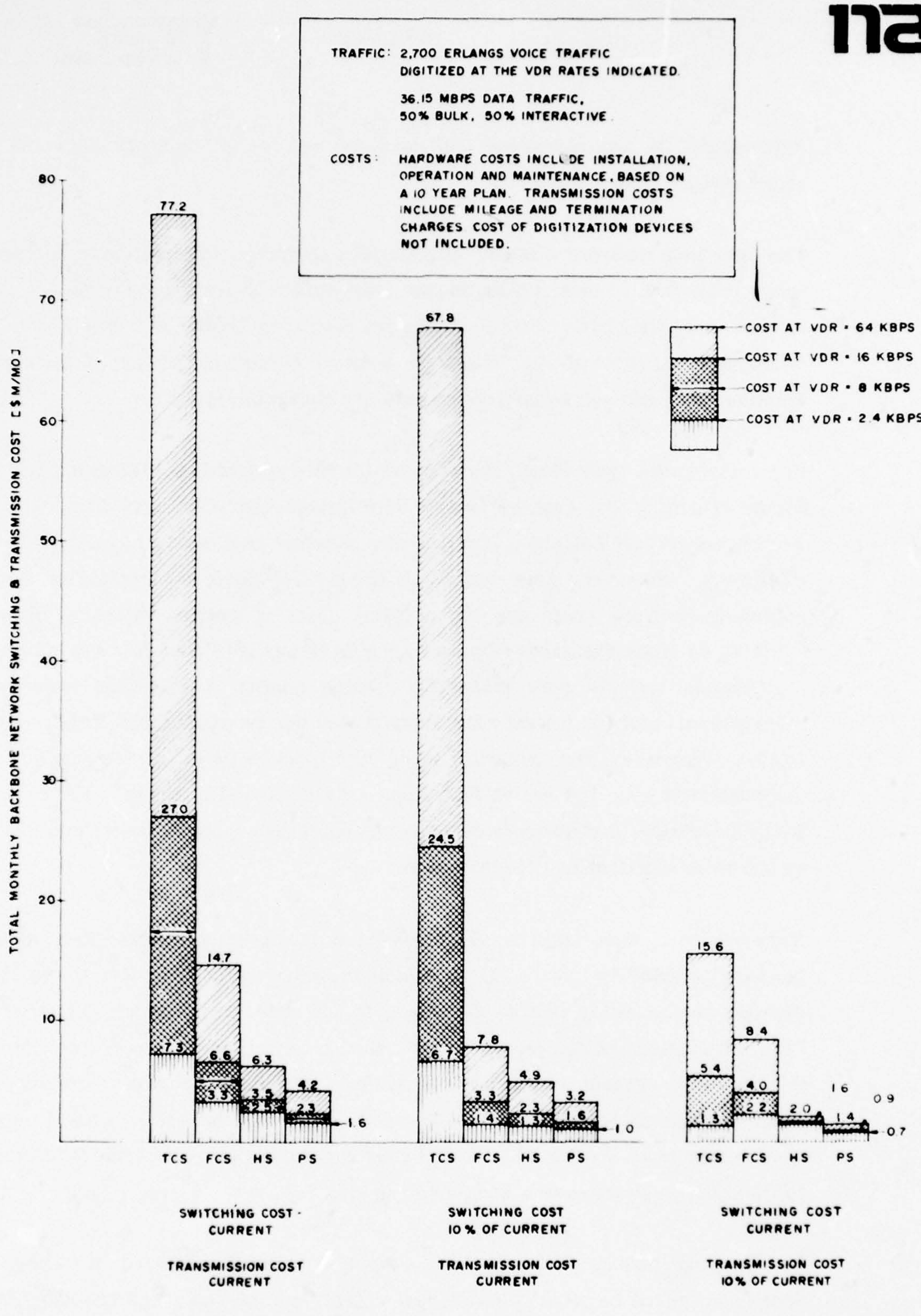
independent of whether voice and data are carried on separate networks or a single integrated network.

- *The backbone network costs of alternatives to the packet-switching technology range from 30% to over 1700% higher than packet switching. Packet switching remains superior to the other technologies even if switching or transmission costs decrease by a factor of ten. Backbone network cost as a function of technology, element cost, and voice digitization rate are shown in Figure 2.*

- *For any network technology, the vocoder bit rate adopted by DOD is a significant factor affecting the cost of future DOD integrated voice and data networks. Traditional circuit switching can gain the greatest cost savings by using low rate digitizers. However, even with 2.4 Kbps VDR devices, traditional circuit-switching network costs are higher than costs of packet-switching networks utilizing 64 Kbps digitizers (Figure 1). It is recognized that low bit rate voice digitization systems may encounter speech quality degradation under noisy environments and the lowest rate devices may not be acceptable throughout the DOD. However, the superiority of the packet-switching technology was demonstrated over the entire (2.4 Kbps - 64 Kbps) VDR range. Furthermore, both the relative and absolute cost savings achieved by packet switching increase as the voice digitization rate increases.*

- *Network cost was found to be insensitive to parameter variations such as: blocking probability (.04 to .1) for which the network is engineered, end-to-end average packet delay (within 200 msec to 600 msec), and priority alternatives. This conclusion holds for each of the alternative network technologies. Additionally, several cases were examined where voice packet delays were constrained to be 50 msec (rather than 200 msec). These lead to packet network cost increases of 1 - 3% and showed that the packet network cost is insensitive to the average delay over a wide delay range.*

- *The moving boundary frame management strategy in hybrid switching was demonstrated to be slightly more cost-effective than the fixed boundary frame management strategy. However, the cost difference appeared to be insignificant with an upper bound of 5% within the range of parameters investigated.*



MONTHLY BACKBONE SWITCHING AND TRANSMISSION COST AS A FUNCTION OF VOICE DIGITIZATION RATE (VDR), COMPONENT COST, AND SWITCHING TECHNOLOGY (TCS - TRADITIONAL CIRCUIT SWITCHING, FCS - FAST CIRCUIT SWITCHING, HS - HYBRID SWITCHING; PS - PACKET SWITCHING)

FIGURE 2

- *An important factor in hybrid switching is the partition of the traffic between circuit-switched and packet-switched services. With hybrid switching, bulk data applications should either use a longer packet size or be served by the circuit-switched subnet. Design options which use a mix of long and short packets are viable when high bit rate communication channels are used. Such channels are required for high traffic volumes, and thus do not impose additional cost for the systems studied.*

- *Security considerations may dictate that voice digitizers are placed at the subscriber handsets rather than at the backbone nodes. This implies that the total cost of the voice digitizers may become an appreciable component of the total system cost. Under this option, the absolute cost savings of the packet-switching technology with respect to any of the alternatives is expected to be larger than the values obtained because of the ability to achieve substantial savings in the local and regional distribution networks under the packet-switching technology.*

- *While detailed security issues were not investigated, if link encryption is used to protect the backbone communication channels, packet switching requires less encryptors (and hence lower cost) because the packet-switching networks require fewer links to meet traffic requirements.*

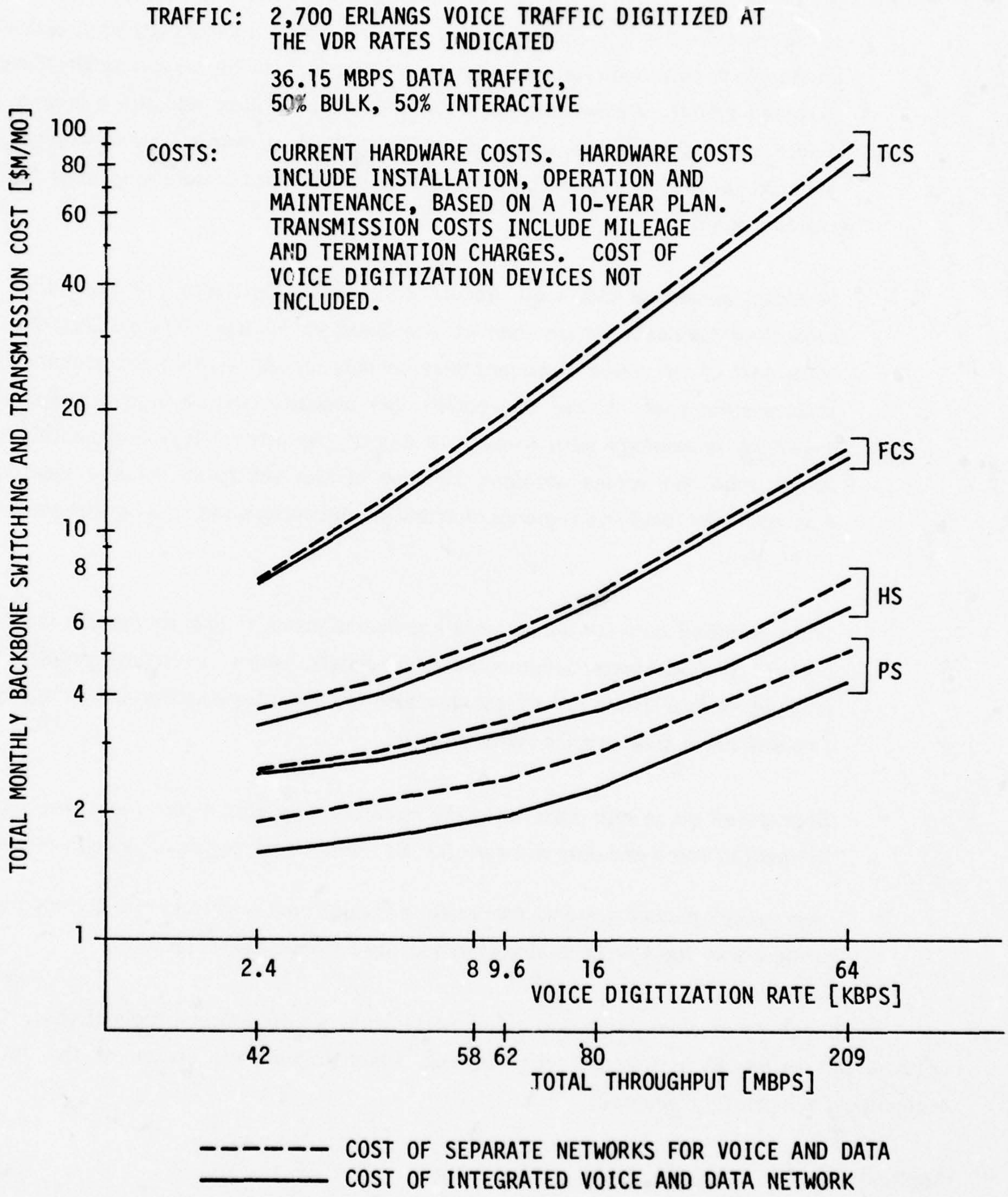
- *Segregated voice and data networks result in only slight cost increases over an integrated voice and data network for all the network technologies considered.*

- *Segregated packet systems for voice and data cost less than integrated systems using either the hybrid or circuit-switching technologies (Figure 3).*

The above conclusions are based on economic analysis of network technologies. Other factors, not reflected in the cost comparisons, which impact the choice of the network technology, are briefly discussed.

Applications:

The packet-switching technology is more suitable for applications involving message dispatching to multidestinations and conferencing. The advantages would be reflected



INTEGRATED VERSUS SEGREGATED VOICE AND DATA NETWORKS AS A FUNCTION OF VOICE DIGITIZATION RATE (VDR) AND SWITCHING TECHNOLOGY (TCS - TRADITIONAL CIRCUIT SWITCHING; FCS - FAST CIRCUIT SWITCHING; HS - HYBRID SWITCHING; PS - PACKET SWITCHING)

FIGURE 3

in the cost had such applications been included in the study. A further advantage of using packet switching for conferencing is the ability to sustain conference connectivity in the presence of link outages.

Priority and Precedence Levels:

Provision of priorities in a circuit-switched network environment requires dedication of facilities to high priority customers (overdesign) or the need to preempt low priority calls in progress under high load conditions. In the latter case, preempted subscribers may place additional burden on the system by redialing. Packet switching can readily accommodate a variety of priority schemes without dedication of transmission resources. The impact of high load high priority traffic on low priority subscribers is longer packet delays, rather than lack of connectivity.

The packet-switching technology can accommodate different access and transport priorities. For example, subscriber A may have higher access priority (ability to establish and sustain communications) than B, yet lower transport priority (no criticality in delivery delay).

Interoperability:

Packet switching is inherently a more suitable vehicle for communications using various media, technologies, and systems (interoperability). With this technology, interoperability is accomplished via "gateways" which interface different networks. Interoperability is expected to be a significant problem during the evolution of DOD communications to an integrated system, in particular, if reliance on existing facilities is to be maximized. Furthermore, interoperability is expected to be a continuous requirement for communications between subscribers in strategic and tactical systems.

Security:

An integrated DOD communications system is expected to provide message security by end-to-end and/or link encryption. One of the design objectives in providing security is the protection of system performance (availability and responsiveness). It is noted

that switching technologies which establish and dedicate end-to-end resources are more vulnerable with link encryption techniques using link synchronization where the receiving crypto derives key synchronization by counting characters in the received data stream. Once the encryption devices lose synchronization (e.g., by short duration jamming), reestablishment may require a relatively long period of time. Naturally, messages using a dedicated circuit will be lost but more significantly, the end-to-end dedicated circuits which utilize the desynchronized link may have to be reestablisned.

Risk:

The circuit-switching technology is relatively simple and well established, and thus the use of circuit switching minimizes the risk of development and implementation. Although, the long-term lowest cost network technology alternative is packet switching, analog and digital circuit switching are expected to be used during the transition period.

VI. DISCUSSION AND FURTHER RESEARCH

The results of this study initially appear quite surprising and perhaps nonintuitive. Thus, it is instructive to point out several additional factors related to the study.

- Since line costs were examined on the basis of tariffs and not costs to a common carrier, it should not be assumed that the conclusions automatically translate to the common carrier environment. Our conclusions relate to the large user who leases tariffed lines and leases or purchases hardware.

- The fact that traditional circuit switching has such poor cost-performance characteristics should be obvious. Traditional circuit switching performs extraordinarily poorly for interactive data applications because of dedication of channel capacity to users during idle periods, and performs poorly for voice applications because it does not detect and eliminate silences from speech. For example, in several cases packet and traditional circuit-switched systems designed to carry only voice traffic were examined. For these cases, costs ranged from approximately equal at very low rates of digitization to circuit-

switching systems costing about 38% greater than packet switching at high digitization rates. With data traffic added, the performance of traditional circuit switching rapidly deteriorates.

- The costs of hybrid switching, while greater than packet switching by 30% - 64%, could be reduced by incorporating speech silence detection methods. Hybrid switch costs would then increase because of increased switching complexity, but the decrease in line costs should result in reduced total hybrid-switching system costs. However, if the appropriate silence detection methods were used, the difference between hybrid and packet switching would probably become a matter of semantics rather than technology. That is, the operation of hybrid switching will be quite similar to that of packet switching, and the cost differences would depend upon the specific implementations of the two schemes.

- If the potential cost savings of the packet or hybrid-switching technologies are to be realized, a detailed examination of the transition issues to be encountered in evolving from current circuit-switched voice networks must be performed. The examination of this issue is of importance because the compatibility of existing communications technologies is not a solved problem. To the extent that low rate voice digitization networks are required to interface with higher rate systems (either domestically or abroad), higher near-term costs than the costs projected in the report may be encountered.

While conducting this study, new problem areas were identified. These problems are recommended for further study with the objectives of uncovering the risks in the conclusions and quantitative results, as well as broadening the study into local and regional distribution and more detailed protocol formulations. Among the areas recommended for further investigation are:

- Further investigations and comparison of hybrid-switching and packet-switching technologies under more detailed protocol scenarios. Although the ranking of these two strategies was consistent throughout the study, the quantitative differences were not extremely large. Furthermore, the hybrid-switching technology may provide a natural evolutionary path for evolving from circuit networks towards a total packet-switching technology.

- Investigation and comparison of local distribution strategies for hybrid and packet-switching networks.

- Investigation of the most appropriate partition between local distribution and backbone networks for hybrid and packet switching.

- Investigation of postulated evolution strategies from existing systems to integrated voice and data communication systems.

- Study of alternative concepts for network and message security in an integrated voice and data network.

- Study of the survivability and reliability of integrated voice and data systems under the packet and hybrid-switching strategies.

PREFACE

This document constitutes Network Analysis Corporation's Final Report for the Project: Integrated DOD Voice and Data Networks. The Project, which was conducted over an approximately two-year period, investigated the cost and performance of alternative strategies capable of satisfying the DOD communication requirements likely to exist in the 1980's and beyond. Three fundamental problems are addressed:

- The economics of serving voice and data applications on common integrated communications systems.
- The comparison of alternative switching technologies for integrated voice and data networks.
- The cost-effectiveness of alternative voice digitization rates and strategies.

Alternative network technologies capable of satisfying DOD requirements in the projected timeframe are identified and examined in detail to project their costs when operating in an environment representing DOD voice and data communication requirements.

In this report assumptions, results, conclusions and recommendations regarding the most cost-effective alternatives for future DOD communication systems are reported. To develop these results, extensive efforts in modeling, analysis and design were conducted over an 18-month period by NAC. These efforts are described in NAC's Semiannual Reports to ARPA and are not repeated here.

Because of the scope of the Project, the Project was organized into the following subprojects, under the overall direction of the principal investigators:

- Circuit-switching technology for voice and data.
- Hybrid-switching technology for voice and data.
- Packet-switching technology for voice and data.

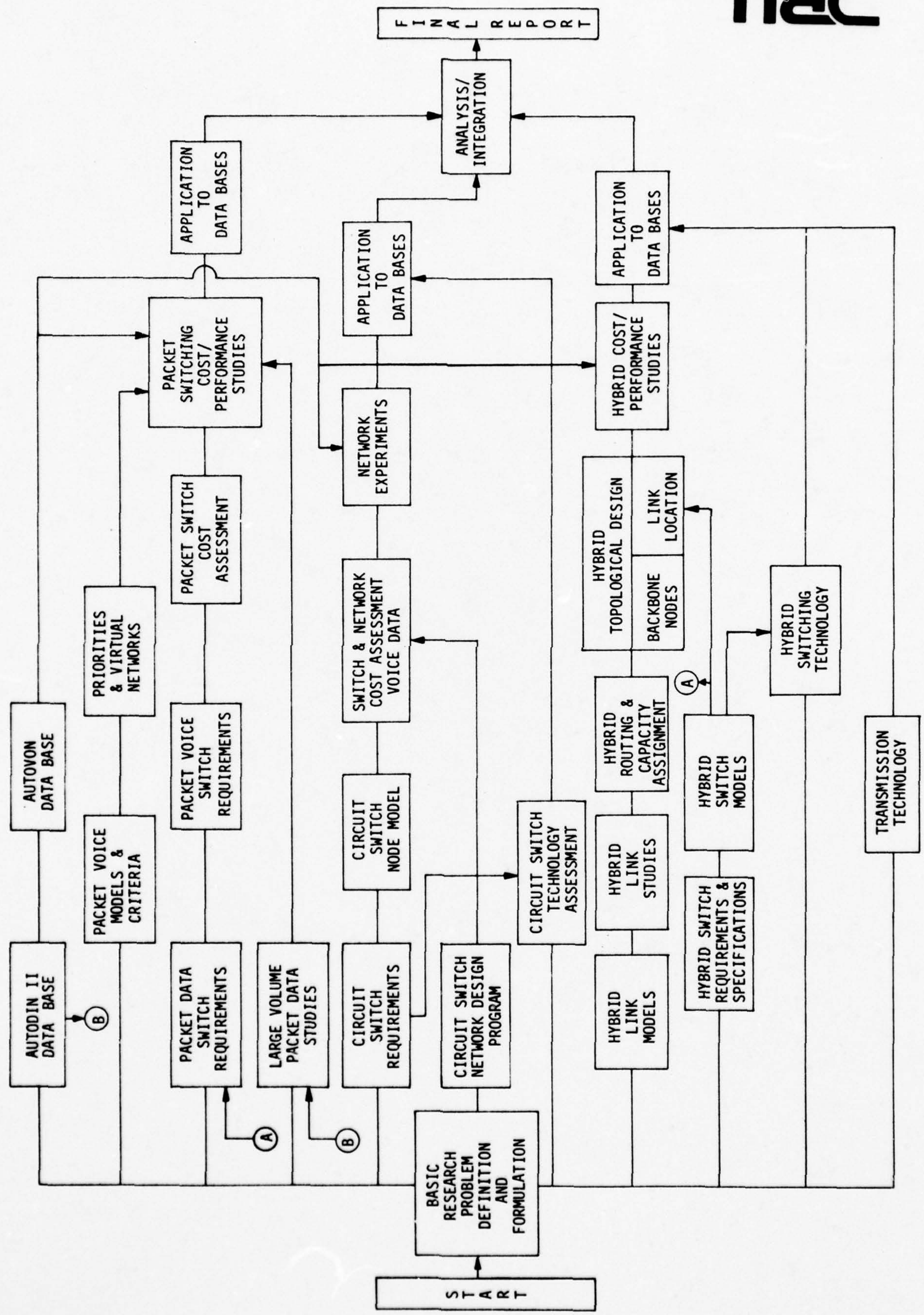
Tasks for each subproject included research, modeling, algorithm and computer program development, and detailed tradeoff studies for the switching technology investigated. These

tasks and the interaction between the subprojects are shown in the diagram below in the form of a PERT chart.

During the first six months of the Project, efforts were oriented towards formulating the detailed objectives of the study, formulating the methodology for comparing the alternative network technologies, identifying the significant parameters which could impact the comparisons, generating voice and data requirements data bases and extensive literature surveys. The research on the subprojects then proceeded independently for most of the study period. During this second period, detailed models and computational tools were developed for protocols, switching devices, and network analysis and design. These models were used to conduct cost/performance tradeoffs for each technology. In many cases, alternative realizations of each network technology were investigated.

The detailed comparison of the alternative network technologies was accomplished during the last six months of the study. During this final period, substantial interaction among subprojects was necessary to ensure that the data bases, cost scenarios and the network performance measures were identical for each of the studies conducted to compare the technologies.

This report is organized as follows: The operational models, data bases and assumptions utilized in the study are described in Chapters 1 and 2. Chapter 3 discusses major results relating to the comparison of the technologies. Chapter 4 provides a detailed discussion of many of the important characteristics and findings for each candidate technology. Chapter 5 summarizes major conclusions and areas suggested for further effort. Appendix A describes open problems and issues concerning the switching technologies studied. Finally, Appendix B provides a short glossary of major terms.


START
BASIC RESEARCH PROBLEM DEFINITION AND FORMULATION
AUTODIN II DATA BASE
AUTOVON DATA BASE
PACKET VOICE MODELS & CRITERIA
PRIORITIES & VIRTUAL NETWORKS
PACKET DATA SWITCH REQUIREMENTS
PACKET VOICE SWITCH REQUIREMENTS
PACKET SWITCH COST ASSESSMENT
LARGE VOLUME PACKET DATA STUDIES
PACKET SWITCHING COST/ PERFORMANCE STUDIES
APPLICATION TO DATA BASES
CIRCUIT SWITCH REQUIREMENTS
CIRCUIT SWITCH NODE MODEL
SWITCH & NETWORK COST ASSESSMENT VOICE DATA
NETWORK EXPERIMENTS
APPLICATION TO DATA BASES
CIRCUIT SWITCH NETWORK DESIGN PROGRAM
CIRCUIT SWITCH TECHNOLOGY ASSESSMENT
HYBRID LINK MODELS
HYBRID LINK STUDIES
HYBRID ROUTING & CAPACITY ASSIGNMENT
HYBRID TOPOLOGICAL DESIGN
BACKBONE NODES
LINK LOCATION
HYBRID COST/ PERFORMANCE STUDIES
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APPENDIX A

TECHNICAL CONSIDERATIONS IN THE ANALYSIS, DESIGN AND OPERATION OF VOICE AND DATA NETWORKS

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THE PROBLEM: INTEGRATED DOD COMMUNICATIONS

1.1 INTRODUCTION

This report presents the results of an economic analysis of alternative network strategies for DOD voice and data communications requirements. The study was motivated by the emergence of new communications requirements and by recent advances in computer and communications technologies. These developments created the conditions under which the sophisticated operational techniques considered in the study have become feasible, quantifiable, and hence capable of a comprehensive study.

Major Department of Defense networks are evolving into digital communications systems [SIGNAL, 1977]. Such systems will enable a higher degree of interoperability between the strategic Defense Communication System (DCS) and tactical systems, the provision of digital secure voice for a larger subscriber base, and the opportunity to support secure voice and data applications on a common integrated communications system.

The objective of the study is to evaluate alternative switching strategies for future integrated *DOD voice and* data networks. Three fundamental problems are addressed:

- The economics of serving voice and data applications on a common integrated communications system.

- The comparison of alternative switching technologies for integrated voice and data networks.

- The cost-effectiveness of alternative voice digitization rates and strategies.

Results of studies regarding cost-effective future DOD communication network options are provided. The sensitivity of the results are tested with respect to traffic variations, switching and transmission costs, and network performance constraints. The significant variables which affect the recommendations are identified and quantified. Furthermore, the cost/performance tradeoffs in integrated voice and data networks under each of the alternative switching technologies are evaluated.

The intent of this study is to identify and quantify network technologies which demonstrate long-term low operating costs. This forms a necessary basis for determining

the most cost-effective evolution for DOD communications. It is recognized that transition problems and their associated costs may be other important decision factors determining the specific evolutionary path. While determining these transition costs was not among the objectives of this study, the study does provide a framework and a target technology which enables detailed evolution planning and cost analysis.

Network analysis techniques have only recently reached the state of sophistication where studies of this scope are feasible. The conclusions and recommendations are based on detailed modeling. The computational tools developed for this study utilize detailed protocol scenarios and traffic profiles to evaluate both the cost of communications channels and the cost components of switching nodes.

At the outset, it is noted that the significance of various factors affecting the cost comparison of alternative telecommunications systems may be different from preconceived ideas or intuitive notions based on previous analyses, because such analysis efforts have concentrated on limited scope problems, traffic volumes, and traffic characteristics. For example, in the particular case of ARPANET, the message delivery delay constraint is a significant factor in determining total network cost because relatively high capacity (50 Kbps) channels must be used to meet a .2 second average delay constraint even when throughput requirements do not necessitate channels of such high capacity. On the other hand, at the high traffic levels considered in this study, high capacity channels are automatically required to satisfy throughput constraints. Hence network cost under these conditions is much less sensitive to variations in the delay requirements.

1.2 MOTIVATION

Emerging DOD communications requirements and recent advances in communications technology which motivated this study are summarized in this section. An assumption is made that a digital technology will be employed in future DOD networks, with the analog voice waveform being digitized prior to transmission over the network.

The advantages of digital transmission include:

- Greater immunity to interference, such as noise and cross talk.
- Compatibility and ability to serve voice and data traffic with a common integrated system.
- Capability to apply digital encryption/decryption techniques.

A major requirement for future DOD voice communications is the ability to provide secure communications from origin to destination for a large group of users. (Existing secure facilities such as the AUTOSEVOCOM wideband network would prove prohibitively expensive when extended to a large subscriber population.) Apart from ordinary voice and data communications applications, future DOD requirements may also include:

- Conferencing
- Multidestination message dispatching
- Computer generated voice response
- Automatic speaker authentication
- Computer recognition of speech content.

The integration of heterogeneous traffic categories into a common system is desirable because of the economies of scale in switching and transmission available from modern industrial manufacturing processes. Integration also offers the capability to dynamically

share transmission and switching facilities and has the capability to accommodate new applications which must access different types of data or voice processes. Most man-machine data communication is extremely bursty in nature, as for example in time-sharing and query-response applications. Indeed, all real-time communications which involve a human in the loop is of necessity bursty in nature. Conversational (real-time) speech is also of a bursty character. Shared transmission and switching facilities allow more efficient utilization of these facilities in bursty environments and consequently provide opportunities for significant cost reductions over the systems of the past.

In the past, most communication systems used dedicated transmission facilities which were not efficiently utilized. The rapid decrease in computer hardware cost over the last 20 years allows modern communication systems to take advantage of the burstiness of the requirements to achieve better utilization of transmission facilities. This can be generally accomplished by dynamically sharing transmission facilities, by using them only when information is being sent, by compression techniques, by error detection and correction techniques, etc.

Three general switching technologies and their variations are evaluated in this study. The switching technologies considered are: circuit switching, packet switching, and hybrid (circuit-packet) switching. Each switching technology accommodates either independent voice or data applications separately or integrated voice and data requirements. Some specific recent developments which make sophisticated switching techniques feasible and which are a prerequisite for the implementation of complex DOD integrated networks are:

- Successful demonstration of the feasibility of the packet-switching technology for data communications.

- Computer and communications cost trends which indicate that the price of computing (switching) has been decreasing much faster than the price of communication (transmission). In the recent past, computing cost has decreased by a factor of ten every five years, while communications cost has decreased at a much slower rate of a factor of ten over 22 years [ROBERTS, 1974]. Furthermore, no spectacular breakthroughs are expected in the cost of communications in the next decade [FALK, 1975].

- Digital transmission and multiplex equipment for microwave systems is becoming much cheaper than equivalent analog equipment [FALK, 1975]. This motivated the assumption of the digital technology in the study.

- Recent advances in low bit rate speech processors. Prime examples are the Quintrell effort supported by NSA, low bit rate low cost device research sponsored by ARPA, and the ANDVT project at NRL. A survey of the state of the art in voice digitization techniques and devices is given in [OCCHIOGROSSO, 1978].

1.3 THE TRAFFIC DATA BASE

The traffic data base was constructed to reflect future DOD voice and data communications requirements. However, the network technologies were investigated under large variations in the traffic data base in terms of traffic volume and the composition of voice and data traffic.

The traffic data base model used was derived from the present DOD voice traffic on the AUTOVON voice system and a scaled model of data traffic projected for the AUTODIN II data network. AUTOVON (Automatic Voice Network) and AUTODIN (Automatic Digital Network) are switched subsystems which are components of the DCS (Defense Communications System). The projected traffic volume of AUTODIN II is varied whereas the traffic distribution pattern is assumed unchanged.

Voice traffic intensity is measured in Erlangs (E) whereas data traffic is measured in Megabits per second (Mbps). The average voice load in Erlangs is computed by multiplying the average call origination rate by the average holding time per call. An average load in Erlangs is equivalent to the average number of circuits that will be occupied by voice subscribers. The voice traffic is assumed to be digitized prior to transmission over the network and is characterized as a bit stream in the automated network design tools. The throughput requirements of the voice traffic are measured in bits per second when the analog voice waveform is converted to digital form for transmission. The throughput requirements so generated depend on the voice digitization rate. Furthermore, an activity factor must be associated with a pair of subscribers engaged in a voice conversation. An activity factor of 50% is assumed in the study. That is, each speaker is assumed to be active (speaking) or silent (listening) 50% of any time interval. (The events where both speakers simultaneously speak or are both silent are not taken into account in the quantitative investigations.)

The nominal gross traffic requirements are 2,700 Erlangs (E) of AUTOVON voice traffic, and 36.15 Mbps scaled AUTODIN II data traffic. At present, the projected near-term volume of AUTODIN II data traffic is relatively low (approximately 1.8 Mbps), compared to the AUTOVON voice traffic. Use of such low volumes would prevent exposing significant cost and performance tradeoffs for integrated voice and data communications requirements. Furthermore, since this study addresses architectures and requirements for DOD communications systems likely to exist in the mid-1980's and beyond and since data communications traffic is expected to grow at a faster rate than voice traffic, a scaled

version of projected AUTODIN II traffic volumes was developed for this study. It is not the objective of the report to predict future DOD data communications traffic. However, simple calculations reveal that the 36.15 Mbps volume would be reached after 16 years at an annual growth of 20%, or after 11 years at an annual growth of 30%. Hence this level of traffic would not be surprising in the late 1980's to mid-1990's.

Data traffic is assumed to be composed of bulk data transfer applications and interactive applications. The nominal volume composition assumes 50% bulk and 50% interactive but the mix is varied over a wide range for sensitivity analysis.

In addition to the nominal data traffic of 36.15 Mbps, system costs are obtained for data throughputs of 11.6 Mbps, 86.8 Mbps, and 202.4 Mbps. Moreover, cost and performance for voice load requirements of 675 Erlangs and 1,350 Erlangs (25% and 50% of the AUTOVON load) are also investigated. The voice digitization rates considered vary from 2.4 Kbps to 64 Kbps for an active speech source. These combinations of traffic and voice digitization rates reults in consideration of digital traffic ranging from 3% voice and 97% data to 94% voice and 6% data.

Apart from the user data and voice traffic to be accommodated by the networks studied, the networks must carry a variety of control, protocol and signaling messages. The volumes and pattern of this overhead traffic depend upon the switching technology, communications protocols, and traffic characteristics. For example, the volume and pattern of messages for circuit setup and disconnection depends on the average voice holding time (60 sec to 180 sec considered) and the routing algorithm for circuit switching. Overhead traffic volumes and patterns are computed by automated network analysis and design tools developed for the study and are based on explicit detailed models of network operation.

NETWORK TECHNOLOGIES AND ASSUMPTIONS

2.1 DEFINITION OF SWITCHING TECHNOLOGIES

A complete definition of all the relevant terms appropriate to the advanced study of networks and switching technologies would require an extensive volume of textbook length. It is assumed the reader is acquainted with network terminology and concepts; only concepts and terms which are not extensively used in the literature are defined. A short glossary of terms is provided in Appendix B.

Three switching strategies are evaluated and compared. These strategies, circuit switching, hybrid (circuit-packet) switching, and packet switching, are compared with respect to separate voice networks and data networks as well as integrated networks accommodating both voice and data. The circuit and packet-switching techniques are applied to both voice and data. The hybrid-switching systems handling voice and data traffic use circuit switching for voice, and packet switching for interactive data applications. Bulk data applications are evaluated under both the packet-switched and circuit-switched approaches.

The switching techniques studied are described in the subsections that follow. The circuit-switching strategies operate by switching of <u>transmission facilities</u> and are characterized by dedication of transmission facilities and reservation of switching capacity for the duration of a call. The packet-switching techniques, on the other hand, are characterized by switching of <u>messages</u> rather than transmission facilities and consequently no dedication of transmission facilities takes place.

2.1.1 The Circuit-Switching Techniques

2.1.1.1 Circuit-Switched System Operation

A circuit-switched system is composed of a signaling system which performs all the functions associated with connection setup, clear down and monitoring, and the call carrying system used by subscribers once an end-to-end circuit has been established.

Signaling conveys the information needed so that a switched telephone network can interconnect one subscriber with any other. Signaling tells the switch that a subscriber desires service and gives the switch the data necessary to identify the distant subscriber desired to properly route the call. It also provides certain status information (busy tone, dial

tone, ringing tone, congestion, etc.). Metering pulses for call charging are also part of the signaling function [FREEMAN, 1975].

When the telephone goes "off-hook," a switch is closed in the telephone set completing the loop to the origination switch and a request for line seizure takes place. Upon seizure, a dial tone is returned, informing the subscriber that the switch is available for receiving address information. The address information provided by the calling subscriber is used in signaling messages to identify and dedicate an end-to-end circuit to the destination subscriber. This is the circuit setup process.

Circuit setup can be accomplished on an end-to-end basis via "origination office control" or on a link-by-link basis by "progressive routing." In the former case, not all the address information is exchanged by tandem (intermediate) backbone switches while setting up the circuit. (For example, the last four digits of a seven digit telephone number need only be exchanged between the origination and destination switches.) Progressive routing is assumed in the study, where all the information for circuit establishment is contained in the signaling message. Thus if blocking on a primary route occurs because of unavailability of circuits, alternate route identification proceeds from the node which contains the signaling message. The link-by-link protocol for transporting signaling messages uses error detection and automatic retransmission if a positive acknowledgment for the signaling message is not received. When either party "hangs up" at the end of information exchange, a signaling message is propagated which releases the end-to-end dedicated circuit.

Of particular significance to this study are the traffic levels and pattern of signaling messages and the network topology and capacities used to accommodate this traffic. The traffic is computed by automated design tools using the offered Erlang load, the routing algorithm, and other information. The model used for signaling traffic assumes dedicated link capacities for signaling - forming a signaling system known as Common Channel Interoffice Signaling (CCIS). Figure 2.1 shows schematically the two overlayed networks, the signaling network and the "call carrying" network. The signaling network is an image of the call carrying network - this is known as Associated Node Signaling. An associated node signaling system is modeled in the study (in general, the two networks may have different topologies).

The call carrying network modeled consists of full duplex digital circuits at a bit rate equal to the voice digitization rate. When a circuit has been set up, an end-to-end circuit is dedicated to subscribers and the switching nodes are initialized to transfer information from the incoming link to the outgoing link. The detailed operation of a circuit-switched network

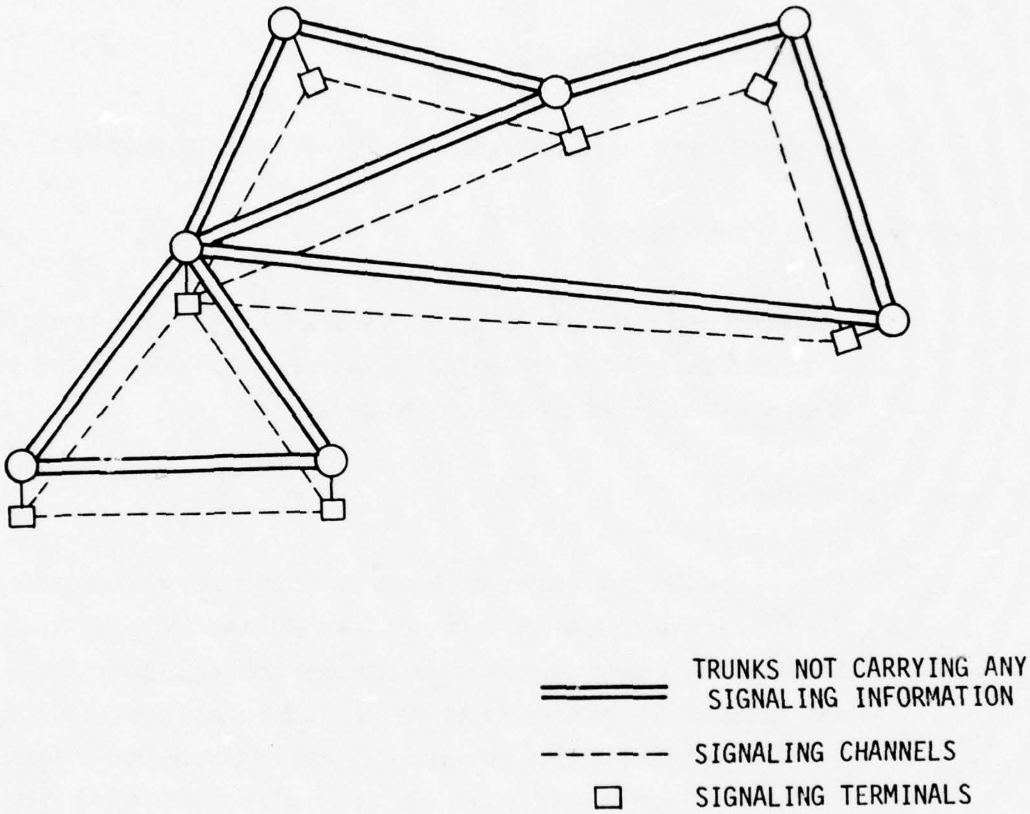


FIGURE 2.1: NETWORK WITH COMMON CHANNEL INTEROFFICE SIGNALING (CCIS) ASSOCIATED NODE SIGNALING

depends on the switching and transmission technology implementations. Information communicated using this technique may be stored and forwarded on a character-by-character basis when traversing a switching node. In contrast to the packet-switched mode, however, the delay of the circuit-switched information (during the communication period) when traversing a switch is virtually constant and independent of switch load.

2.1.1.2 Circuit-Switching Options

The following three circuit-switching techniques are evaluated in the report:

Traditional Circuit Switching:

An end-to-end circuit is set up for a pair of voice or data users. The end-to-end transmission facilities are dedicated to users for the duration of use. The circuit is disconnected when either party hangs up.

Fast Circuit Switching:

Voice and bulk data applications use the traditional circuit-switching technique. For interactive data users, a circuit is established for every message when ready to be sent and disconnected after message delivery. Specifically, the circuit is not dedicated to the user during his idle "think time" period; however the channel capacity not used during circuit setup and disconnection is taken into account. This concept assumes advanced digital switches enabling the setup of a circuit in 140 msec so that delay requirements for interactive data applications can be satisfied. It is likely that this technology will be available for the DOD in the timeframe contemplated by this study.

Ideal Circuit Switching:

This scenario is almost the same as fast circuit switching except that circuit setup and disconnection are assumed to occur in zero time. Hence no channel capacity is wasted during setup and disconnection. While ideal circuit switching is not physically realizable, it is considered in order to obtain a lower bound on transmission cost for the circuit-switching technology.

Traditional circuit switching need not necessarily be less economical than fast circuit switching or even ideal circuit switching because of the tradeoff between switching and transmission cost. Although the transmission capacity required in the ideal case is smaller, there are many more circuit setups and disconnections which increase required switching capacity and hence cost.

2.1.2 *The Hybrid-Switching Techniques*

Hybrid (circuit-packet) switching has been considered in many previous studies [COVIELLO, 1976], [GITMAN, 1977], [OCCHIOGROSSO, 1977], [COVIELLO, 1975], [FISCHER, 1976], [GTE, 1975], [BARBACCI, 1976], [SHUTZER, 1976], [BLACKMAN, 1976], [CICCHETTI, 1975] as a desirable technology for integrating voice and data applications. This arrangement was partially motivated by studies [MIYAHARA, 1975], [ESTRING, 1975], [ROSNER, 1975] which demonstrated that circuit switching is cost-effective for traffic characterized by long holding time while packet switching is cost-effective for bursty traffic, characterized by short messages and long pauses between messages. However, "short" and "long" are relative terms which depend upon the technology realizing the switched system. A traffic source is considered bursty in this study if the time to establish and release an end-to-end circuit in the network plus the message transmission time is shorter than the time interval until next message generation.

The operation of a hybrid-switched system and the specific options studied are presented in the next subsections.

2.1.2.1 *Hybrid-Switching System Operation*

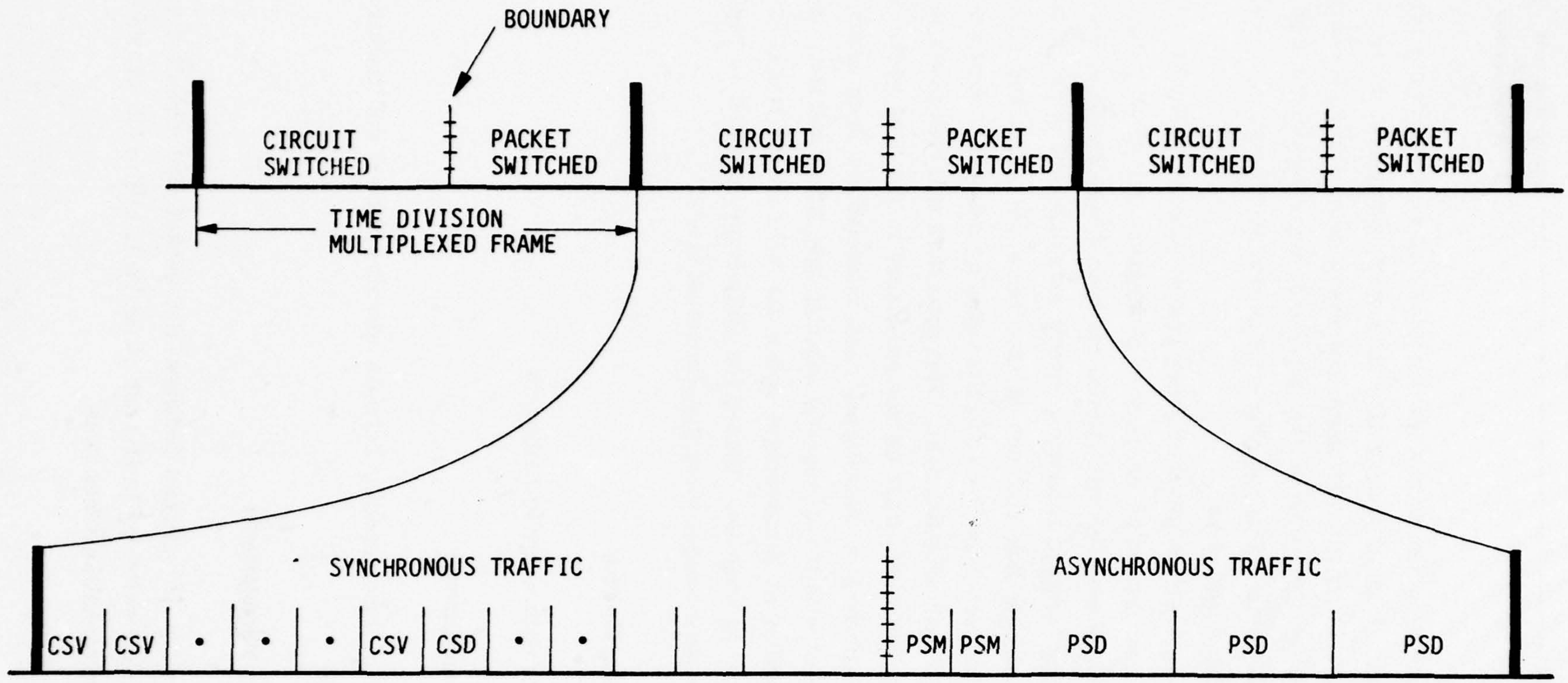
The switching and transmission facilities of the network are dynamically shared between traffic using the circuit and packet-switched modes of operation. That is, the capacity of a communication link can be dedicated to a circuit-switched connection at one instant and carry packet-switched traffic at another instant. Similarly, the switching node contains all programs and functions needed to perform either circuit or packet switching and the switching processor is dynamically shared by all functions. Its "instantaneous" load depends on the mix of traffic requirements, the priorities, etc., at the particular time.

A communication channel linking two nodes in a hybrid-switched system utilizes a time division multiplexed master frame format. The frame is defined as a constant time interval throughout the entire backbone network [COVIELLO, 1975],[BARBACCI, 1976]. Network links may have different channel capacities, resulting in a different number of bits per frame. For example, a frame of 10 msec duration on a T1 carrier (1.544 Mbps) will contain 15,440 bits. A voice circuit using a digitization rate of 8 Kbps will require an 80-bit slot in each frame. The absolute frame times in the network need not be synchronized. For example, start of frame time on different links emanating from a single switching node or the start of frame times on the two directions of a full duplex link need not be the same.

Figure 2.2 shows an exemplary link and frame structure. The frame contains a boundary which partitions link capacity between the circuit-switched synchronous traffic and the packet-switched asynchronous traffic. In the example shown, voice and data (e.g., bulk data transfer applications) are multiplexed on the circuit-switched region of the frame, while signaling messages for circuit setup and disconnection and data for interactive applications use the packet-switched region of the frame. The frame boundary is a software parameter and the capacity partition of the frame to circuit-switched and packet-switched regions need not be fixed or identical on different network links. Moreover, the circuit or packet-switched regions need not be contiguous.

The circuit-switching operation of the hybrid switch is identical to the previously described traditional circuit switching. The packet-switching technique modeled in the study is similar to the scheme presently implemented in the ARPANET. Specifically, a message is fragmented at the origination node into fixed size blocks, headers are appended to each block to form packets, and the packets are transported to the destination. The packet headers include the origination and destination addresses, a sequence number or absolute byte count to enable unique reassembly into the original message, priority, and other information. Packet transport is accomplished via a store-and-forward protocol with error detection and retransmission between adjacent nodes (hop-by-hop). Each packet is transported independently to the destination, with individual packets belonging to the same message following possibly different paths to their destination. Message reassembly takes place at the destination node prior to message delivery to the destination subscriber.

The postulated operation of a hybrid switch is similar to hybrid-switching nodes currently under investigation [GTE, 1975],[BARBACCI, 1976]. Apart from the necessary routing and control messages, the input traffic stream to a hybrid switch includes store-and-forward packets, digitized synchronous information using a circuit-switched connection in



CSV - CIRCUIT SWITCHED VOICE SLOT
CSD - CIRCUIT SWITCHED DATA SLOT
PSM - PACKET SWITCHED SIGNALING MESSAGE SLOT
PSD - PACKET SWITCHED DATA SLOT

FIGURE 2.2: EXEMPLARY HYBRID-SWITCHING CHANNEL STRUCTURE: TIME DIVISION MULTIPLEXED FRAME

progress, and signaling messages requesting new circuit-switched connections (or disconnections). The physical input (from communication channels to random access memory) and output operations can be performed by peripheral processors using Direct Memory Access (DMA) capabilities. The switch CPU provides the mapping of incoming slots on input frames to outgoing slots on output frames. This mapping is a function of message type, destination, facility occupancy, and other parameters.

The header of each correctly received incoming packet is processed by the CPU which determines the outgoing link depending on packet destination, its priority, and routing tables. The packet is then queued for transmission on some future frame of the outgoing link. An incoming signaling message requesting circuit establishment is processed by the CPU to determine the outgoing link and slot in the frame via which the message will traverse. A circuit-switched slot is assigned and the signaling message is forwarded to the next node to proceed with path establishment. This procedure will result in a new frame structure for the outgoing link which must be communicated to the next node. Once the end-to-end circuit is established, a mapping at each intermediate node associates the incoming link, frame and slot with the appropriate outgoing link, frame and slot. There is no error detection or correction at intermediate nodes for information transmitted via a circuit-switched connection in progress. Hence, the CPU is not required to perform any additional processing of these messages while the connection is held.

2.1.2.2 Hybrid-Switching Options

Two hybrid-switching options are investigated:

Fixed Boundary Frame Management:

The partition of link capacity between circuit-switched and packet-switched traffic is fixed.

Moveable Boundary Frame Management:

While a boundary is assigned between the packet and circuit transmission capacities, packet-switching traffic can dynamically utilize idle channel capacity assigned to the circuit-switched mode.

A detailed investigation of the moveable boundary strategy is necessary because the savings in transmission cost that result from the moveable boundary strategy could not have been estimated *a priori*. Although the definition of the options considered refers to dynamics of channel utilization, the two alternatives also require switching nodes with different capabilities; this is taken into account in the modeling of the switching nodes.

2.1.3 *Packet-Switching of Voice and Data*

The motivation for examining the packet-switching technology for voice and data communications is discussed, followed by the description of system operation for the specific packet-switching techniques investigated. The focus of the discussion is on packet voice communications, since the technique used for packet switching of data is the same as in the hybrid-switching technology.

2.1.3.1 *Motivation for Packet Voice Communications: Silence Detection*

Packet switching is an efficient way to prevent transmission capacity consumption during the silence periods in the voice conversation. It is often assumed that voice traffic is characterized by long (60 seconds to 300 seconds) holding time. This assumption is true from a "macroscopic" viewpoint since an average voice conversation has this duration. However, it is well known that during conversations, actual active speech by each user is followed by periods of silence and thus utilizes the full duplex channel only a fraction of the time. A voice source is characterized by active speech periods (producing a so-called talkspurt) separated by silent intervals of approximately equal duration; furthermore, only one speaker is usually active at any specific time. Hence, dedicating an end-to-end circuit to a pair of subscribers for the entire interval of conversation is wasteful of channel capacity. In the past, dedicated channels for voice communications were appropriate because the processing cost was too high to take advantage of the silences in speech.

During the past two decades, numerous analog and digital techniques for compressing the conversations of a number of speakers onto a smaller number of channels have been developed. The earliest strategy was the Bell System TASI (Time Assignment Speech Interpolation) [BULLINGTON, 1959] in which channel capacity is allocated only when appropriate hardware detected that a subscriber was actively speaking. Once the channel is seized, the speaker is given uninterrupted access to the channel. During periods of silence,

the channel is relinquished and becomes available to other speakers. Digital variations of the original TASI concept, such as DSI (Digital Speech Interpolation) [CAMPANELLA, 1975] and SPEC (Speech Predictive Encoding) [SCIULLI, 1973] have also been implemented. The above systems "freezeout" speakers when the number of active speakers temporarily exceeds the available channel capacity. This results in clipping and segmentation of certain conversations with an associated loss in intelligibility. Refinements of the TASI concept based on digital encoding techniques whereby the bandwidth per active speaker is systematically reduced to accommodate additional speakers have also been implemented. Two such techniques are APCM (Adaptive Pulse Code Modulation) and VRAM (Variable Rate Adaptive Multiplexing) both developed by the U.S. Army ECOM. In these systems, when the number of active speakers exceeds the channel capacity during "overflow periods," performance degradation is shared among all speakers by reducing the sampling rate per conversation. Thus, no single speaker suffers excessive degradation. Many variations of speech interpolation with priorities and multiplexing of data in speech idle periods have also been proposed.

Despite the bandwidth savings which were achieved by deployment of such systems, their use is restricted to one link. The addressing/routing problems which must be solved in order for systems of this nature to be adopted in a distributed communications network would prove extremely complex, and it appears that their resolution leads naturally to a packet type family of operational procedures. Thus, packetized voice represents a viable scheme for multiple class traffic integration and speech compression within a distributed network.

2.1.3.2 Packet Voice/Data Network Operation

A brief overview of a packet voice network operation and structure is given. Figure 2.3 illustrates a packet voice network and typical packet voice conversation flow. Speech is assumed to be digitized in the subscriber handset but packetized at the backbone switch. When a subscriber handset goes off-hook, high-level protocol functions are invoked in the source switch which subsequently determine the destination address of the called party. Resource allocation may be performed at this time (analogous to a setup interval in circuit-switching networks) for some transport protocols. The precise nature of the user interface protocol (concerning subscriber access attention, signaling, etc.) must be specified as part of the total system design and will vary in complexity depending on the nature of

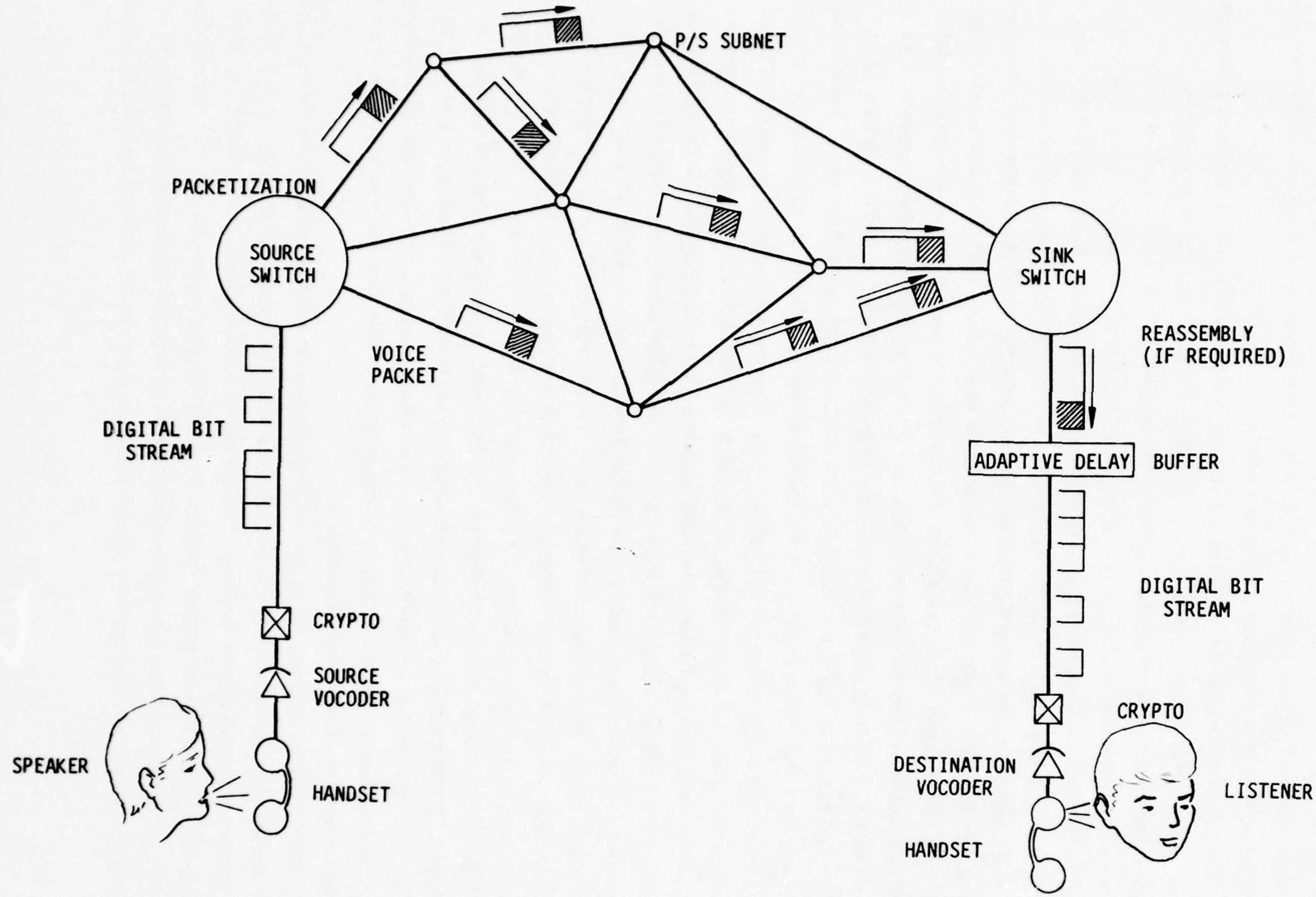


FIGURE 2.3: EXEMPLARY PACKET VOICE/DATA NETWORK AND INFORMATION FLOW

subscriber service features to be supported. After establishment of a logical connection, the source subscriber is notified that speech can commence.

The manner in which the digitized bit stream is created depends on the type of vocoder in use. In general, speech is analyzed at periodic intervals by the source vocoder. Each temporal segment during which the speech is analyzed is called a time window or parcel. In the event the speaker is active, a digitized representation of the speech during that window period is created and transmitted to the backbone packet switch. If the speaker is silent, no information is transmitted from the handset to the switch during the window period. Note that more sophisticated voice digitization devices may not transmit information even when the speaker is active if certain speech parameters (e.g., pitch, gain, reflection coefficients, etc.) have not changed appreciably since the last window period. If end-to-end encryption is employed, the digitized bit stream is also encrypted at the subscriber handset. At the source switch, incoming digital windows are collected together to form a packet. Both the number and nature of the windows placed in a single packet are a function of the protocol. Windows from one speaker or several speakers can be placed in the same packet. In addition, the rules governing packet release (i.e., when a packet can be transmitted through the network) may be time driven, determined by the amount of information presently contained in the packet, or by some combination of these techniques. Once the packet is scheduled for release, a header is appended (containing the appropriate control information), the packet is placed on a channel output queue (selected by the routing strategy) and allowed to proceed to the destination backbone switch. The nature of the routing strategy may be fixed or adaptive. At tandem switches, packet processing a bare minimum (consisting of read-in, header analysis, read-out). Packets arriving at the destination node are analyzed, the header is removed and depending on the transport protocol's operation, reassembly of packets may also be required. Windows which belong to different speakers are routed to the appropriate destination vocoders. At the destination vocoder, the digitized bit stream is decrypted if necessary and the digital representation of the time window is used to create a synthetic version of the original speech.

An important component in the source-destination path is an adaptive-delay buffer. This device may be located in the switch or within the handset depending on the desired distribution of intelligence between the terminal and network. The buffer is used to compensate for delays in packet arrivals to preserve the continuity of the reconstructed speech. A natural consequence of the transmission of any synchronous source over a packet-switched network is that gaps may appear between consecutive packets arriving at a given

destination. If the current window playout period is shorter than the temporal gap between windows, the reconstructed speech will be interrupted. If the incidence and duration of these interruptions becomes too frequent or too long, the reconstructed speech may become unintelligible. The adaptive delay buffer is therefore used as a means of smoothing the temporal gaps between consecutive windows. This buffer causes an artificial delay to be added to the arrival of the first window in a consecutive stream of speech windows destined for the same vocoder. Thus, subsequent incoming windows can accumulate during the artificial delay period so that by the time the first window has been played out, a sufficient backlog of windows will have been created by new arrivals. This preserves the continuity of the synthesized speech. The delay should also be made adaptive with respect to the network delay, in order to avoid buffer underflow or overflow. If the network delay is long and the buffer delay is short, the buffer can underflow thereby generating interruptions in the reconstructed speech. If the network delay is short but the buffer delay is long, the buffer can overflow thereby causing the loss of certain windows. Finally, in the event the duration of speech interruption becomes excessive, the destination vocoder may repeat the contents of the last window to preserve speech continuity. The choice among any of these buffer control/smoothing options—loss versus delay, and insertion versus interruption—is a function of the destination delivery protocol and at present is the subject of active research [NEMETH, 1976], [LINCOLN LABS, 1976].

2.1.3.3 Packet-Switching Options

Under an integrated packet-switching approach, both voice and data are accommodated by the store-and-forward procedures. However, different packet sizes and different transport protocols may be used for data and speech. The packet voice protocol options considered are:

Fixed Path Protocol (FPP):

When a voice call originates, a signaling message is propagated to the destination to set up a path for the call. The path setup involves setting appropriate pointers at tandem switching nodes to determine the outgoing link for every input voice packet. No channel capacity is reserved or switch capacity dedicated. Voice packets follow the fixed path. When either party hangs up, the path is released.

Path Independent Protocol (PIP):

In this protocol, no path is set up. Each voice packet is transported to the destination independently of other packets of the same conversation. Packets can use alternate routes as appropriate.

Under PIP, no setup/allocation of end-to-end resources or reservations at intermediate nodes are made. During periods of communication, packets are created at the speaker's vocoder, released into the network, routed over a dynamically selected path and delivered to the listener's vocoder. PIP operation allows successive packets belonging to the same talkspurt to traverse different sets of links. Packets can thus be received out of order because of varying delays encountered over different paths. The path independent protocol provides no formal reassembly mechanism and does not guarantee sequential packet delivery to the destination node. A distinct advantage associated with the path independent protocol is that if an adaptive routing strategy is used, voice packets that are part of the same conversation do not necessarily use identical paths. Hence, communication is more robust in the presence of failures or under a directed attack. The PIP technique essentially provides only the most basic transport capabilities. This mechanism is a good candidate for internetworking applications between different packet-switching systems. However, PIP inefficiencies may exist in networks using low bit rate voice digitization devices, since the time required to create a large packet can be excessive. For exceptionally long packets, the packet creation delay could exceed the network delivery delay. Consequently, a strong motivation exists for keeping the packet size small. Because of the comparatively large header required by PIP (e.g., full source and destination addresses, etc.), the information content of a voice packet must be large to reduce the transmission overhead contributed by the header.

An alternative strategy which reduces the amount of information required in the header is the Fixed Path Protocol (FPP) approach. The FPP technique guarantees sequential packet delivery. However, a setup time interval (analogous to circuit switching) is required to establish a logical path between source and destination. Once a logical path is established, this path is maintained for the entire conversation. Although this places an additional operational burden on all switches, voice packets now require a reduced amount of addressing information during transmission. The use of an abbreviated header (indicating to which conversation the packet belongs) is adequate for an intermediate switch to perform

routing. Consequently, the global transmission overhead is decreased, and shorter voice packets can be used to reduce the packet creation time. However, the FPP approach is significantly less robust in the presence of link or node failures, and in such cases, recovery procedures must be initiated. Moreover, without detailed analysis, it is not clear which form of overhead—transmission due to large header in the case of PIP or increased operational complexity in intermediate switches in the FPP approach—results in the higher cost system.

2.2 COST MODELS

No attempt is made to predict cost trends of computers or communication facilities. Cost trends depend not only on technology but also on cultural and regulatory factors. In particular, technological developments depend upon demand as much as upon the capability of the technology. For example, the widespread adoption of low VDR devices would result in significantly lower per unit costs than those currently predicted. Existing computer and communications costs are used in the study and the major results are sensitivity tested with respect to large variations in switching or transmission costs.

Cost factors are based on current procurement estimates for tariffed communication lines and hardware. Communication line costs include mileage and termination charges. Hardware cost factors include purchase price, installation, initial support, operations, maintenance, and amortization. Cost factors not considered are network management costs, the security costs of specially cleared switches, operational personnel, and the cost of encryption devices.

2.2.1 Transmission Cost Model

The transmission cost model used in the study is:

$$LC(i) = a_1 \left[a_2 + D(i)^{\alpha_1} \right] \left[\frac{C(i)}{a_3} \right]^{\alpha_2} \qquad (2.1)$$

where

LC(i) = Total monthly cost for link i [$/mo]
D(i) = Length of link i [miles]
C(i) = Channel capacity of link i [Kbps]

The parameters a_1, a_2, a_3, α_1, and α_2, are estimated to obtain best fit to specific service offerings. LC(i) takes into account the mileage charge as well as the fixed end charges for a specific capacity offering. The above equation was found to be sufficiently general to represent a large variety of tariff structures. It is assumed that terrestrial lines are exclusively used for all systems studied.

The Digital Data Service (DDS) offering is used in the study; parameter estimation was performed to fit the DDS tariff. The resulting formula is:

$$LC(i) = 0.61\,[\,40.05 + D(i)^{0.873}]\;C(i)^{0.728} \tag{2.2}$$

2.2.2 *Switching Cost Model*

The switch cost model is a function of processing, memory size, and the cost of channel interfaces. The general formulae used to compute the purchase price of a backbone switching node is:

$$SC(i) = b_1\,P(i)^{\beta_1} + b_2\,M(i)^{\beta_2} + \sum_j b_{3j}\,C_i(j) \tag{2.3}$$

where:

- $SC(i)$ = Total cost of switch i [$]
- $P(i)$ = Processing capacity of switch i [10^6 instructions/sec]
- $M(i)$ = Memory size [10^6 (32 bit) words]
- $C_i(j)$ = Channel capacity of outgoing link j.

The parameters b_1, b_2, b_{3j}, β_1, and β_2 are estimated using current switching technology. The parameter b_{3j} represents the cost of the channel interface and is a function of the channel capacity.

The following components are taken into account in computing processing capacity and memory size:

<u>Processing Components</u>

- Operating System Overhead
- Circuit-Switching Rate
- Data Packet-Switching Rate
- Voice Packet-Switching Rate
- Total Character Transfer Rate
- Hybrid Switch Complexity
  - Frame Rate
  - Circuit and Packet Rates Per Frame
  - Moving Boundary Complexity

Memory Components

Overhead Memory

Storage for Tables

- Circuit and Packet Routing Tables
- Calls in Progress Tables

Storage for Store-and-Forward Data

Processing capacity is the most significant component of the switch cost. The processing capacity is computed for every switch in the network, taking into account the throughput of various message types and communications protocols. For example, the signaling message rate through a switch depends on the routing algorithm and upon the blocking probability for which the network is engineered. In particular, if a network is engineered for a higher blocking probability, a higher degree of alternate routing results which contributes to a higher signaling throughput requirement and consequently, to a higher switching cost.

Table 2.1 shows key parameters used for computing switch processing capacity. In addition, a 20% operating system overhead was assumed and a 15% higher processing per frame in the hybrid-switching technology for the moving boundary frame management strategy than for the fixed boundary case. Figure 2.4 shows sample costs of computer systems of major U. S. manufacturers as a function of processing capacity. This is part of the data used for estimating parameters in the cost formulae. The cost function resulting from the parameter estimation is:

$$SC(i) = 0.35\, P(i)^{0.65} + 0.3M(i)^{0.9} + \sum_{j} b_{3j}\, C_i(j) \qquad (2.4)$$

The formulae used for computing switch processing power and memory size are (for convenience, we omit reference to switch i):

$$P = (1 + OVH)\{CPS \cdot NC + PVPS \cdot NPV + PDPS \cdot NPD + CHPS \cdot WPCH \cdot NCH + NF \cdot FPS \sum_{j=1}^{N\ Links} [1 + \alpha \cdot CPF(j) + \beta \cdot KPF(j)]\} \qquad (2.5)$$

TABLE 2.1: PARAMETERS USED FOR COMPUTING SWITCH PROCESSING CAPACITY

NUMBER OF INSTRUCTIONS	TYPE OF PER SWITCHING NODE OPERATION
10,000	Circuit switch processing of a signaling message for circuit setup
5,000	Message processing for fixed path set up under the fixed path packet voice protocol
600	Data packet processing under packet switching and hybrid switching
400	Voice packet processing under the path independent packet voice protocol
100	Packet voice processing for a packet using the fixed path protocol
100	Frame management processing (per frame) in hybrid switching
2	Character transfer processing (assuming DMA)

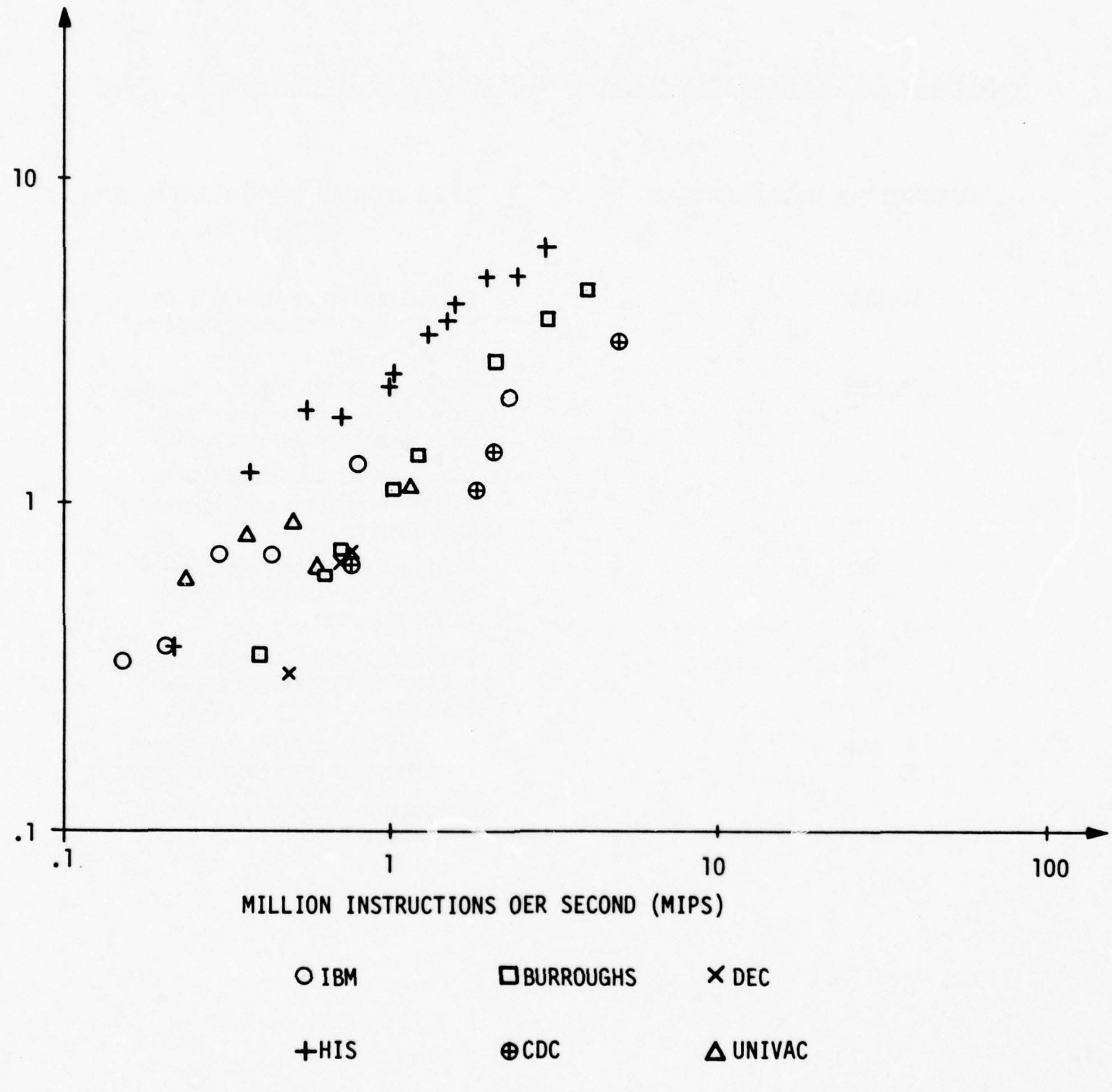


FIGURE 2.4: SAMPLE COMPUTER COSTS AS A FUNCTION OF MIPS (EXISTING SYSTEMS)

Where

OVH	=	Operating system overhead factor
CPS	=	Rate of call setup and disconnection at the switch
NC	=	Number of instructions for processing a call setup (or disconnection) signaling message, including the identification of the next link (routing)
PVPS	=	Rate of voice packet throughput at the switch
NPV	=	Number of instructions to process a voice packet header, including its routing
PDPS	=	Data packet throughput at the switch
NPD	=	Number of instructions to process a data packet header
CHPS	=	Character transfer rate
WPCH	=	Words per character (in our case ¼)
NCH	=	Number of instructions per character transfer
NF	=	Number of instructions for frame management in hybrid switching
FPS	=	Rate of frames at the switch (depends on the frame time)
N Links	=	Number of links at the switch
CPF(j)	=	Average number of circuit-switched slots per frame in the j^{th} outgoing link of the switch

KPF(j) = Average number of packets per frame on the j^{th} outgoing link from the switch

α = Overhead complexity factor in moveable boundary hybrid switching per circuit slot

β = Overhead complexity factor in moveable boundary hybrid switching per packet.

Note that not all terms are non-zero for all switching strategies. For example, the last terms, starting with NF, is used only for hybrid switching, and the terms multiplied by α and β are used only for the moveable boundary hybrid-switched strategy. The equation for computing memory size is:

$$M = MOS + \{\sum_j \sum_k PKPS(k, j) \cdot PL(k) \cdot \bar{T}(k, j) \cdot WPB\}$$

$$+ \{\sum_j \sum_k N(k, j)A(k)\} + \{CKRT + PKRT + CIPS\} \qquad (2.6)$$

Where

MOS = Memory requirement for the operating system and communications software

PKPS(k,j) = k^{th} packet class arrival rate on the j^{th} outgoing link at the particular switch

PL(k) = Average packet size of the k^{th} packet class

$\bar{T}$(k, j) = The time (in terms of transmission time on link j) that the packet of class k will be stored in the switch

WPB = Words per bit (1/32)

N(k, j) = Number of slots of VDR_k on link j at the particular switch

A(k) = Storage requirements for a call in progress

CKRT = Circuit routing table size

PKRT = Packet routing table size

CIPS = Table space for calls in progress

The second term in Equation (2.6) gives the buffer requirement for packets, the third term gives the circuit-switched calls in progress under the circuit and hybrid-switching technologies, and the last term gives table space for routing and for recording connections in progress. The packet class refers to a voice packet or one of several data packet classes. The time that a packet of a particular class needs to be stored in the system takes into account the expected time to receive an acknowledgment for classes where an acknowledgment is used; however, no analysis to guarantee an overflow below a given probability was done in determining this value.

As presented above, there are many factors which are taken into account in computing the cost of every switch in the network. Given the flows of various traffic types of network links, Equations (2.5) and (2.6) are used to compute the processing power and memory requirement of every switch taking into account the throughput of the various traffic types (signaling messages, voice packets, data packets, calls in progress, etc.) and the particular switching strategy. Finally, Equation (2.4) is used to compute the switch purchase price, taking into account processing power, memory and channel interfaces. The comparison of switches for different network technologies, in isolation, without considering the network as a whole is rather difficult and will not provide insight into the comparison of the switching technologies. However, when we compare the costs of the alternative technologies, we specifically focus on the cost of switches of the different technologies and explain the reason for the relative costs of such switches.

Apart from current switching and transmission costs, the sensitivity of network cost to component hardware and transmission costs is derived using the following two cost scenarios:

1. Switching Cost - 10% of current
   Transmission Cost - current.

2. Switching cost - current
   Transmission Cost - 10% of current.

Conversion Factor: Communications channels are leased, hence their cost is recurring and given in dollars per month. The switch costs are given in purchase price and are converted to monthly cost using cost analysis practices of the Defense Communications Agency (DCA). The conversion factor is based on a 10-year amortization plan; it includes installation charge at 20% base cost, initial support charge at 67% base cost, and a 10-year operation and maintenance cost at 47% base cost. It assumes a redundancy factor of 1.5; a capital factor of about 5% per year, based on 10% annual interest over ten years. Using the above analysis results in a Conversion Factor of 0.0438 from Purchase Price to Monthly Cost.

2.2.3 Cost of Voice Digitizers

Low bit rate voice digitizers that are of particular interest for DOD systems are presently under development. Although there exist low VDR devices for commercial use, the purchase prices quoted (e.g., $10,000 for a 2.4 Kbps device) are not representative of their potential large volume cost. Furthermore, with recent advances in LSI technology, the cost of such devices is expected to decrease significantly in future years. Since this report addresses DOD systems in the mid-1980's and beyond, when current costs would be totally inappropriate, the cost of VDR devices is parameterized with analysis oriented towards determining the cost at which VDR devices become economical for various switching strategies and digitization rates. The conversion factor used for switching nodes is used to convert capital cost to recurring monthly cost for voice digitizers.

2.3 NETWORK STRUCTURE AND PERFORMANCE

The assumptions on network structure and network performance are presented. This section also discusses the alternatives for location of voice digitization devices evaluated in the study. The general design methodology is presented at the end of this section.

2.3.1 Network Structure

The evaluation and comparison of switching technologies is performed for backbone networks with backbone switching nodes at the eight AUTODIN I switch locations. The backbone voice traffic corresponding to these locations is determined by assigning the current AUTOVON switch traffic requirements to the eight backbone nodes according to the nearest distance criterion. Network links and their capacities are obtained by automated network design techniques using the minimum cost criterion subject to satisfying network performance requirements. However, a two-connectivity (each node connected to at least two other nodes) requirement is imposed to guarantee network reliability.

The number of backbone nodes is held constant in the present investigations since previous studies [NETWORK ANALYSIS CORPORATION, 1977],[NETWORK ANALYSIS CORPORATION, 1976] have shown that the optimum number of backbone nodes for comparable throughput levels range from five to twelve, and that the cost differences in this range are insignificant. Moreover, well-designed networks with as many as 30 distributed switches have been shown [NETWORK ANALYSIS CORPORATION, 1977],[NETWORK ANALYSIS CORPORATION, 1976] to lead to networks with communication and hardware costs only a few percent above the minimum. Thus, the number of backbone nodes is not a critical issue from a communications efficiency perspective and this number can be determined based on other criteria such as cost of secure switch facilities and network survivability.

Detailed analyses of the cost of local distribution networks are not conducted in this study. However, preliminary analyses of local distribution network technologies result in the expectation that the results of detailed local distribution design studies will not change the conclusions of the current investigation. This expectation derives from the following points. For voice digitization at the backbone nodes, local access lines would be similar under the circuit, packet or hybrid technologies. Furthermore, if voice digitization occurs at the handset (or at a local building telephone branch exchange), the circuit-switching technology

should lead to equal or greater local access line costs than the packet-switching technology. Costs would be equal if digitization occurs at high data rates since an equal number of access lines would be required for either technology. At low digitization rates, the natural multiplexing capabilities of packet switching would tend to increase the effective utilization of the local access lines and hence decrease the number and cost of the lines required. Previous studies [NETWORK ANALYSIS CORPORATION, 1977],[NETWORK ANALYSIS CORPORATION, 1976] have shown that the cost of local distribution networks is on the order of 50% of the total system cost. These previous results can be used to estimate the absolute cost differences between the alternative switching technologies on a total system basis including local distribution networks.

2.3.2 *Location of Voice Digitization Devices*

One of the areas investigated in the study is the cost-effectiveness of incorporating voice digitization devices of various rates into the network architecture. The resulting costs depend on the functional location of the digitization process. Investigations are performed for the following three cases:

1. Backbone network voice requirements are in digital form at a given bit rate. The location and cost of the digitization process is not considered.

2. Voice is digitized at the origination backbone node.

3. Voice is digitized at subscriber handsets.

Under Assumption (1) the absolute backbone network cost differences between alternative network technologies are independent of the location of the digitization process and are not affected by the location of the voice digitizers. Under Assumption (2) low bit rate digitizers are provided in the backbone network with the objective of reducing total system cost. This case is applicable to public voice and data systems or for DOD subscribers who do not require end-to-end encryption. An integrated DOD system may consist of some subscribers with digitizers at the handset and other subscribers whose voice signals are digitized in the backbone network. Assumption (3) relates to the case where all DOD subscriber handsets include voice digitizers. In this case, while the total cost of digitizers

would increase because of the larger number of units required, savings could be generated by reducing the cost of local access, by using techniques such as multiplexing, concentration and packet switching.

2.3.3 Network Performance

In the circuit and hybrid-switching technologies, the networks are engineered on a blocking basis for voice and on a delay basis for data. Blocking implies that a percentage of voice calls will be rejected by the system via a busy tone because of unavailability of facilities. Data subscribers under the circuit-switching technology are assumed to automatically redial every 10 msec when blocked, until an end-to-end circuit is established. The packet-switching network is engineered on a delay basis for both voice and data subscribers.

All networks are engineered for the following nominal performance values:

1% end-to-end blocking for circuit switched voice
200 msec end-to-end packet delay for interactive data users and packet voice
600 msec end-to-end packet delay for bulk data applications.

The percentage of blocked calls for which the networks are engineered is varied from 0.4% to 10%, and the end-to-end packet delay is varied from 200 msec to 1 sec and the corresponding network costs are calculated to determine the effects of these performance requirement variations. Note that the delays considered are originating backbone node to destination backbone node. Since packetization is assumed to occur at the backbone switch, local access delays depend only on the transmission speed of the local access lines and will usually contribute only a small additive factor.

An issue of some controversy is the precise delay measure to use for packetized voice. While in this study average delay is used, other measures such as 95^{th} and 99^{th} percentile have been proposed. Coviello, et al, [COVIELLO, 1977] in a paper which includes a thorough discussion of the delay issue, suggests that the delay for the 95^{th} percentile is about twice the average delay when three packet switches are traversed from origin to destination. The possible consequence of adopting a more stringent delay constraint (such as the 95^{th} percentile) is that higher network costs might be necessary in order to insure that the 95^{th} percentile of delay does not exceed 200 - 300 msec. To examine this possibility, several

analyses were performed with an average voice packet delay constraint of 50 msec. It was found that backbone transmission costs increased by 1% to 3% for the cases examined. This result followed because only small increments in transmission bandwidth were required to eliminate the network queueing delays, one of the main components of the total end-to-end delay. Consequently, the relationships identified remain valid even if the delay constraint required is made substantially more stringent.

A significant design parameter in hybrid and packet switching is the packet size. Large variations of the packet size parameter are examined. Under the hybrid-switching technology, the range of maximum packet size investigated for bulk data applications is 1,000 bits to 10,000 bits.

The packet-switching technology is investigated with several sizes of information fields and packet headers for voice communications. Headers of 48 bits and 96 bits are considered with the fixed path protocol, and headers of 96 bits, 152 bits and 256 bits are considered with the path independent protocol. The size range of voice packets investigated is 72 bits to 1280 bits, depending on voice digitization rate and protocol option employed. Since a large packet size from a single speaker may not be practical because of the time required to form a packet at a low VDR, a protocol option of "compound packets" was assumed in such cases. Under this procedure, speech windows of several speakers are multiplexed into one packet and demultiplexed at the destination node to prevent excessive delays between packets in the same talkspurt. This reduces packetization delay as well as packet overhead, but algorithms to construct and demultiplex compound packets are then required. The range of packet and header sizes considered for packet voice communications results in a header overhead range of 3.6% to 51.6%.

2.3.4 General Problem Formulation and Design

In this section, we briefly state the problem and outline the subproblems which form the design methodology.

Given:

- A set of switching nodes N and their locations
- Traffic volume requirements (voice traffic matrix in Erlangs and data traffic matrix in Kbps)

- Traffic characteristics, which include:

  - Voice digitization rate
  - Average call holding time
  - Average bulk message size
  - Average interactive message size and average idle time between messages

- Signaling procedure and signaling message size

- Network operation and design parameters, which include:

  - Voice and data switching strategy
  - Communication protocols (e.g., FPP or PIP for packet voice)
  - Routing algorithms
  - Packet sizes for bulk data applications, interactive applications and voice traffic in the case of packet switching
  - Header size for the various packet sizes
  - Priority structure for the traffic categories

- Tolerance values for meeting end-to-end performance requirements

- Cost vs. capacity and distance for terrestrial communications channels:

  $LC(i) = f\,[\,C(i), D(i)\,]$, Equation (2.2)

- Cost vs. processing capacity, storage requirements and channel interfaces for switching nodes:

  $SC(i) = f\,[\,P(i), M(i), C_i(j)\,]$, Equation (2.4)

- Cost of voice digitization devices, where appropriate.

Determine:

- The set of links $A = \{\ell_i\}$
- The channel capacity C(i) for every link in A
- The processing capacity P(j) and memory requirement M(j) for every switching node

which minimizes the total cost:

$$\sum_A LC(i) + \sum_N SC(j) + \text{Cost of VDR devices}$$

such that:

- Traffic volume requirements are accommodated
- End-to-end traffic performance requirements are satisfied (this includes blocking and delay for the various traffic classes)
- Average voice call setup and disconnection delays in circuit and hybrid-switching strategies are satisfied
- Two-connectivity constraint is satisfied.

The design methodology involves iterative application of the solution to the topological problem, link dimensioning and capacity assignment, and the routing problem. The design methods are significantly more complex than those used for either circuit-switched network design or packet-switched network design. Among the factors contributing to complexity are: existence of several traffic classes with different priorities, several message sizes and routing algorithms, the interaction between the voice and data traffic flows, and the complexity of the switching strategies. This resulted in the necessity to develop and automate numerical optimization techniques because many of the subproblems did not lend themselves to closed form solutions. Some of the optimization techniques developed for the hybrid-switching examples are described in [HSIEH, 1978].

COST COMPARISON OF SWITCHING TECHNOLOGIES

3.1 INTRODUCTION

This chapter presents quantitative results for the major strategies investigated in the study. The comparative costs of network technologies as a function of voice traffic and voice digitization rate are given in Section 3.2. This section also analyzes the cost components of each switching technology in terms of switching and transmission costs. The component costs per megabit of traffic are also provided. Section 3.3 provides the results of sensitivity analyses which give total costs of alternative switching technologies under large variations in the price of switching and transmission. The cost-effectiveness of serving voice and data with segregated or integrated networks is discussed in Section 3.4. Finally, Section 3.5 contains results concerning voice digitization rates and strategies. The price breakpoints below which it is cost-effective to incorporate low bit rate digitizers in the backbone network are demonstrated. The total system costs when the digitizers are in the handset are given as a function of number of handsets and the cost of voice digitizers. A hybrid digitization technique, whereby voice is being digitized at the handset for secure voice requirements and in the backbone network for the remaining users is also quantitatively investigated.

For all studies, network technologies are compared on the basis of cost under the assumption of digital switching and transmission. Certain factors such as message and network security or the transition costs are not considered.

3.2 COMPARISON OF SWITCHING TECHNOLOGIES AS A FUNCTION OF VOICE TRAFFIC AND VOICE DIGITIZATION RATE

This section compares the circuit-switching, the packet-switching, and the hybrid (circuit-packet) switching technologies for integrated voice and data applications. The results for each switching technology are first discussed and comparisons are then provided.

The comparison in this section assumes that voice requirements are presented to the backbone network in digital form. That is, the cost of the digitization process is not taken into account. Furthermore, the issue of voice quality is not addressed; for the constraints used, voice is assumed to be at an acceptable quality for each of the digitization rates compared.

Figure 3.1 shows the total monthly cost in million dollars for all the switching technologies as a function of the Voice Digitization Rate (VDR). The current prices of switching and transmission are used to obtain the results shown. The VDR value indicates the maximum bit rate of an active voice source and is assumed the same for all sources. Voice is offered in Erlangs and converted to bit rate throughput requirements by multiplying the number of Erlangs by the voice digitization rate. Hence the VDR impacts both total throughput of the system (in bits per second) and the fraction of digital traffic represented by voice requirements. Total throughput is shown as an alternate horizontal axis in Figure 3.1.

Based on numerous parametric studies it was found that the voice digitization rate is a significant parameter affecting the cost of an integrated voice and data communications system. Figure 3.1 shows that the total switching and transmission cost of circuit-switching strategies is very sensitive to the voice digitization rate.

The cost of digital communications systems carrying voice with VDR as a variable has not previously been exposed. When requirements for secure end-to-end paths are not present, it is cost-effective to convert voice to a low bit rate at the backbone network level. In the DOD environment, which includes some users who require end-to-end security and others who do not, the impact of low VDR is quite significant. The first major conclusion of this study is:

- *The voice digitization rate is the most significant parameter affecting the absolute cost comparison of alternative switching technologies for integrated voice and data communications.*

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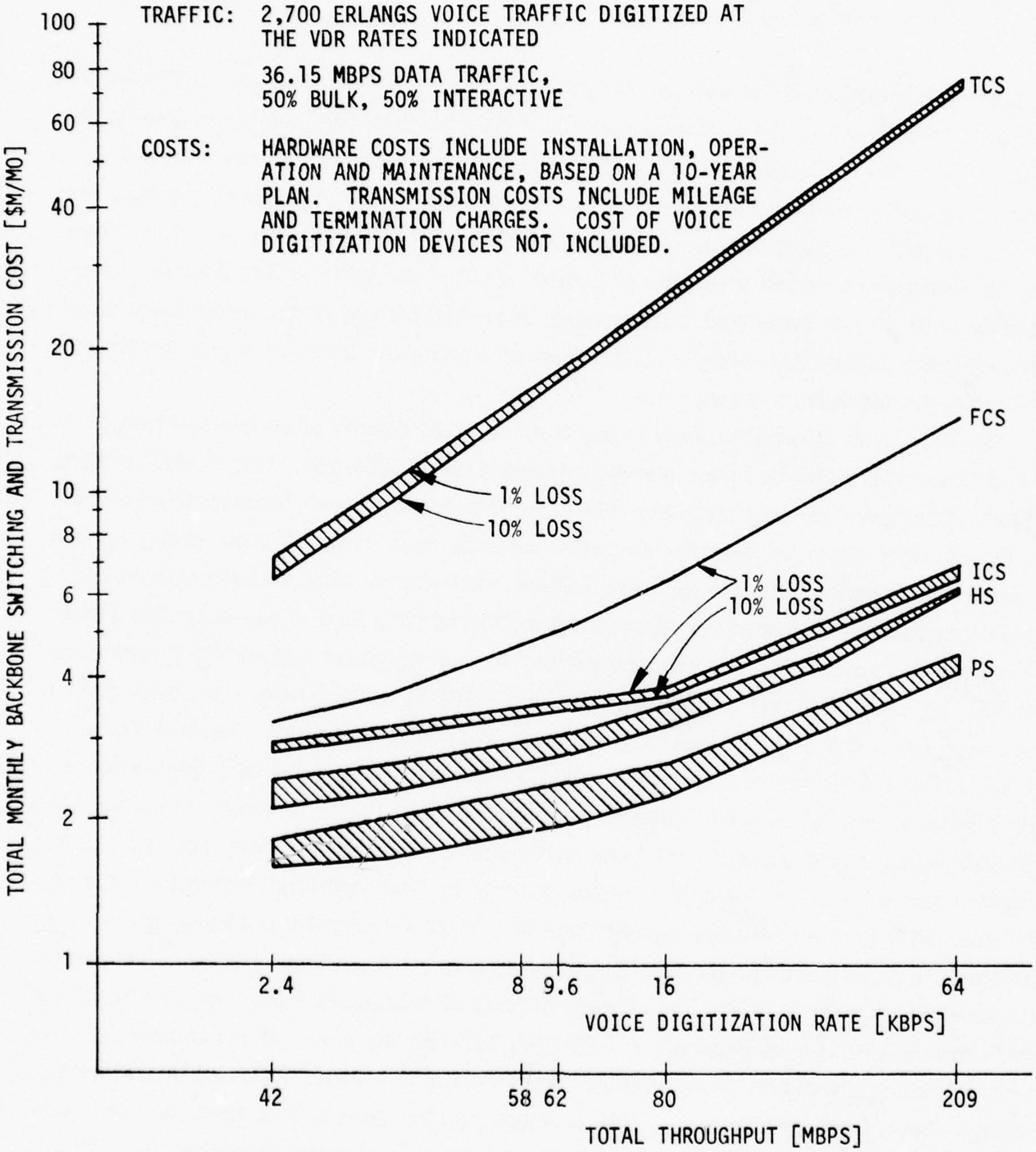


MONTHLY BACKBONE SWITCHING AND TRANSMISSION COST AS A FUNCTION OF VOICE DIGITIZATION RATE (VDR) AND SWITCHING TECHNOLOGY (TCS - TRADITIONAL CIRCUIT SWITCHING; FCS - FAST CIRCUIT SWITCHING; ICS - IDEAL CIRCUIT SWITCHING; HS - HYBRID SWITCHING; PS - PACKET SWITCHING). COST RANGES INDICATE ALTERNATIVE OPERATION SCENARIOS (HS AND PS) OR BLOCKING PROBABILITY RANGE (TCS, ICS).

FIGURE 3.1

3.2.1 Circuit-Switching Technology

The circuit-switching strategies defined in Chapter 2 are compared in Figure 3.1. These are: traditional circuit switching, where a circuit at the VDR capacity is dedicated to a pair of users for the duration of the call; fast circuit switching which takes advantage of the low duty cycle of interactive data users by establishing a circuit for each message when ready to be sent and disconnecting afterwards (a delay of 140 msec is assumed for circuit setup or disconnection); and ideal circuit switching using the same protocol as fast circuit switching with circuit setup and disconnection requiring zero seconds. While ideal circuit switching is not physically realizable, it is examined to obtain a lower bound on transmission cost for the circuit-switching technology.

The duty cycle of an interactive user is assumed to consist of an average idle (think) time of 10 seconds followed by an average message size of 1000 bits. This is characteristic of interactive users sending messages "line-at-a-time" rather than "character-at-a-time." The actual duty cycle of interactive users depends upon many factors including user patterns, the computer system and applications environment (e.g., scientific/engineering applications, business applications, etc.), and the I/O and CPU load of the computer system. The results of a study of traffic characteristics for user-computer interactive processes are reported in [FUCHS, 1970]. The model in [FUCHS, 1970] breaks the man-machine interaction into the events: user generation and transmission of several bursts of characters to the computer, waiting period for computer response, the generation and transmission of several bursts of characters from the computer to the user, user think time and next message preparation, next burst of character transmission from the user to the computer and so on. The results of measurements on four practical systems have shown [FUCHS, 1970] that the average waiting time for computer response is 13 sec, the average user think time to generate the next response is 5 sec; the average number of characters from user to computer is 12 and the average number of characters from computer to user is 119. Converting the measurements in [FUCHS, 1970] to the model of the interactive data traffic of this study results in an average idle period of 9 seconds followed by an average message size of 66 characters. This is close to the parameters used in the study. Furthermore, the average number of message exchanges in a session reported in [FUCHS, 1970] is 192, whereas in this study, 200 message exchanges per session are assumed. The cost of the traditional circuit-switching technology as a function of duty cycle parameters is presented in Chapter 4.

Voice calls are engineered on a blocking basis and data calls on a delay basis. An interactive user is assumed to redial automatically at 10 sec intervals when blocking occurs. Blocking implies that a certain percentage of calls will be rejected by the system because of the unavailability of facilities. End-to-end blocking probability is also referred to as loss. The loss for which the systems are engineered ranges from 1% to 10%, and the average delay for an interactive message ranges from 200 msec to 600 msec, depending on the voice digitization rate.

Among the feasible circuit-switching strategies, fast circuit switching is clearly superior to traditional circuit switching for integrated voice and data networks under current prices of switching and transmission. The cost of traditional circuit-switching increases very quickly with VDR, from 7.28 million dollars per month at 2.4 Kbps to 77.18 million dollars per month at 64 Kbps, for 1% loss. However, the rate of increase is smaller than that of the VDR value, because voice is only part of the traffic accommodated and because of economy of scale in the purchase of switching and transmission facilities. The absolute cost increase primarily results from an increase in cost of the transmission facilities. Although the circuit setup and disconnection load is independent of VDR, the cost of switching increases from .7 million dollars per month at VDR = 2.4 Kbps to 9.3 million dollars per month at VDR = 64 Kbps. This occurs because the expansion of transmission facilities increases two components of the switching cost: the interface cost to communications channels, and the processing resulting from the higher bit transfer rate. Converting these monthly switch costs to purchase prices under the assumption of identical capacity for each of the eight backbone switching nodes yields prices per switch of $2 million at VDR = 2.4 Kbps and $26.5 million at VDR = 64 Kbps. Note that this difference increases rapidly as the voice digitization rate increases. Thus, for the fixed level of voice and data traffic (in Erlangs and Mbps, respectively), the difference is about a factor of two at VDR = 2.4 Kbps and about a factor of five at VDR = 64 Kbps.

The switching cost component of fast circuit switches is much higher than for traditional circuit switching. Nevertheless, since fast circuit switching is less sensitive to the VDR parameter than traditional switching, the switching cost increase from VDR at 2.4 Kbps to VDR at 64 Kbps is from $2.03 to $7.7 million per month. These monthly figures correspond to purchase prices per circuit switch of $5.8 million at VDR = 2.4 Kbps and $22 million at VDR = 64 Kbps. The cost of switching nodes is higher in the fast circuit-switching technology than in the traditional circuit-switching technology at low VDR; the reverse is true at high VDR. The transmission cost is the significant cost component contributing to

the relatively large difference in the total cost between the traditional and fast circuit-switching technologies.

The end-to-end loss does not have a significant effect on network cost. The cost reduction for traditional circuit switching ranges from 4.1% to 9.2% when the loss increases by an order of magnitude from 1% to 10%. There are two main reasons for the relatively small impact of the loss parameter. First, when the network is engineered for a high loss, a higher degree of alternate routing takes place which contributes to an increase in switching cost. Second, for high volume traffic such as in the DOD environment, the channel capacity (number of circuits) needed to accommodate the traffic is very high. The efficiency of large trunk groups is such that only a small percentage of additional trunks are needed to reduce the link blocking probability. Coupled with economy of scale in the purchase of transmission facilities, this results in a relatively small loss effect on the cost of transmission facilities.

Two significant observations can be made from the analysis results of the circuit-switching technology:

- *The total cost of circuit-switching network technologies is not sensitive to the loss probability for which the networks are engineered.*

- *The cost of the traditional circuit-switching technology is more sensitive to the voice digitization rate than the other network technologies. The increase in the voice digitization rate not only penalizes the voice applications but also the interactive data applications which under the assumptions made, occupy voice equivalent channels.*

3.2.2 *Hybrid (Circuit-Packet) Switching Technology*

In this section, the backbone costs corresponding to the hybrid-switching technology using the moving boundary frame management strategy are discussed. Comparisons of alternative implementations of hybrid switching are presented in Chapter 4.

Figure 3.1 shows the range of cost as a function of VDR for hybrid-switching strategies. The upper curve corresponds to the case where only voice is circuit switched and data is packet switched. The lower curve corresponds to the case where both voice and bulk data traffic are circuit switched and the interactive data applications are packet switched. The range between the two curves corresponds to varied mixes of bulk and interactive data

applications - between 0% to 50% bulk out of the total 36.15 Mbps data traffic. The strategy with circuit-switching bulk data applications requires further investigation and additional experiments. This would only be of interest in evaluating alternative realizations of hybrid switching; it would not impact the comparison of alternative network technologies. For hybrid switching it is assumed that all data is being packet switched unless otherwise indicated. It is noted that in the hybrid-switching alternative, no attempt was made to utilize speech compression techniques such as those discussed in Section 2.1.3.1. Such techniques could affect the cost comparisons.

The hybrid-switching designs shown were engineered for a voice loss of 1%. The packet size for interactive data is 800 bits (including header) and engineered for 200 msec average end-to-end delay; the bulk data packet size is 1200 bits (including header) and engineered for 600 msec average end-to-end delay. Progressive routing is assumed for circuit switching and the corresponding signaling messages derived are accommodated as packet-switched data traffic, without priority. For packet switching, adaptive routing is assumed and appropriate network overheads are taken into account in the designs.

The hybrid-switching technology matches the switching concept to traffic characteristics as traditionally conceived; circuits are dedicated to voice users for the duration of the call. As expected, its backbone network cost is well below that of circuit-switching strategies. The switching cost component is higher than for traditional circuit switching but lower than in fast circuit switching; a special contributing factor to the hybrid-switching cost is the switch complexity.

The cost of the hybrid-switching technology increases with VDR but at a slower rate than in the circuit-switching technologies. At VDR = 2.4 Kbps, the total monthly cost is \$2.46 million and at VDR = 64 Kbps, the total monthly cost is \$6.35 million; a cost ratio of 2.58. Most of the increase is attributable to the cost of transmission. The rate of increase in total cost is smaller than anticipated because of economy of scale.

The hybrid-switching technology is examined under variations of data traffic mix (between bulk applications and interactive applications) and under variations in packet size. Some of the detailed results are reported in Chapter 4. The analysis of hybrid-switched networks has shown that cost is sensitive to the mix of data traffic applications and leads to the following conclusions:

- *An important aspect of the design and operation of hybrid-switching networks is the partition of traffic between circuit and packet-switching services.*

- *The most cost-effective strategy under hybrid switching may result when bulk data is handled in a circuit-switched mode and interactive data applications plus voice are handled in a packet-switched mode.*

The last conjecture is motivated by the superior channel utilization obtained by packet-switching voice and interactive data applications and the reduced switching capacity and channel capacity requirements for packet headers when using circuit switching for bulk data applications.

3.2.3 Packet-Switching Technology

Circuit-switching and hybrid-switching technologies require transmission facilities and some switch resources to be dedicated to users; packet switching requires virtually no dedication of resources. Packet switching copes well with traffic burstiness whether data or speech is being communicated. The penalties paid for potentially eliminating all idle capacity are the header overhead appended to each packet and the increased switch processing. Packet speech communication is in an early stage of development; many issues with regard to protocols, error control, routing, etc. are still being studied [NEMETH, 1976], [LINCOLN LABS, 1976]. Consequently, a variety of protocols and header sizes were examined to obtain a range of cost and performance relationships.

The following strategies were used to obtain the range of costs associated with packet designs shown in Figure 3.1:

- Fixed Path Protocol (FPP) with headers of 48 bits and 96 bits, with and without the compound packet protocol option.

- Path Independent Protocol (PIP) with headers of 152 bits and 256 bits under the compound packet protocol option.

The protocol type, FPP or PIP, directly impacts switch cost. In FPP an initial signaling message is propagated to the destination switch to determine a fixed path. It causes the setting of appropriate pointers at tandem (intermediate) switching nodes which determine the outgoing link for every arriving voice packet; however, once the path is established subsequent packets require less processing per switch to use the fixed path.

Under PIP there is no path setup; however, the processing per voice packet at each switch is greater than under FPP. The protocol type also impacts the header size —a larger header is needed for PIP—which increases the transmission cost. The compound packet concept provides for the encoding of speech segments from several speakers into the same packet when the speakers have a common destination switch. The technique seeks to reduce packet header overhead while retaining a small speech packetization delay at the origination switch.

The use of compound packets becomes important at low VDR, where a long delay may be required to collect a packet from a single vocoder, and especially significant when using a path independent protocol involving a relatively large header. The use of compound packets affects both transmission and switching cost. The designs developed are based on a model where a speech segment (window) contains 10 msec of speech; a number of segments is associated with the triplet (vocoder VDR, Header Size, Compound Packet Option). The number of speech segments, the vocoder VDR, and the Header Size determine the packet size and overhead. The results reported in Figure 3.1 include a range of packet overheads from 3.6% (VDR = 64 Kbps, 2 segments, H = 48) to 44.4% (VDR = 2.4 Kbps, 5 segments, H = 96). Hence, the range covered by the designs anticipates a wide variety of practically engineered packet voice and data networks.

The packet voice and data networks are engineered for an end-to-end delay of 200 msec for speech and interactive data packets, and 600 msec for bulk data packets (as in the hybrid switching case).* It is important to note that no optimization is performed in selecting packet speech size. Consequently the total costs should be somewhat lower than those derived. Also the packet speech size varies with the different VDR values.

As a function of VDR, the lower bound of the set of designs shown in Figure 3.1 increases from $1.6 million per month at VDR = 2.4 Kbps to $4.15 million per month at VDR = 64 Kbps; the upper bound increases from $1.86 million per month at VDR = 2.4 Kbps to $4.6 million per month at VDR = 64 Kbps.

3.2.4 *Comparison of Switching Technologies*

Figure 3.1 provides the cost comparison of all switching technologies as a function of the voice digitization rate. The designs compared are for the integrated AUTOVON voice traffic of 2700 Erlangs and a scaled AUTODIN II data traffic of 36.15 Mbps. The switching

* In several cases, costs were calculated at a 50 msec average delay. In these cases costs were found to be 1 - 3% greater than for the nominal 200 msec constraint.

and transmission cost models are those derived in Chapter 2; the transmission cost procedure conforms to the DDS tariff structure and rates and the switching cost corresponds to current prices of computer systems. The cost comparison of alternative switching technologies leads to the following conclusions:

- *The packet-switching technology is superior to all other switching technologies for the entire range of the voice digitization rate.*

- *The traditional circuit-switching technology is inferior to any of the other alternatives.*

Table 3.1 gives sample costs comparing traditional and fast circuit-switching strategies, the hybrid-switching strategy with circuit-switched voice and packet-switched data, and the packet-switching strategy using the path independent protocol with a 152 bit header. Using the packet-switching cost as the base, the following relationships result:

- *The hybrid-switching technology is more costly than packet switching by 56% and 50% for VDR = 2.4 Kbps and 64 Kbps, respectively.*

- *The fast circuit-switching technology is more costly than packet switching by 106% and 250% for VDR = 2.4 Kbps and 64 Kbps, respectively.*

- *The traditional circuit-switching technology is more costly than packet switching by 356% and 1740% for VDR = 2.4 Kbps and 64 Kbps, respectively.*

3.2.5 Switching Cost Components

There exists a tradeoff in telecommunications between communications and computation since more sophisticated processing performed at switching nodes usually results in a reduction of transmission facilities. Different switching concepts demonstrate a different breakdown of switching and transmission cost components at the optimum (minimum cost) design. To reflect this tradeoff, percentage of switch cost is shown in Figure 3.2 with voice digitization rate as a parameter. The first observation made is that traditional circuit switching is characterized by the smallest switching cost component and fast circuit

TABLE 3.1: BACKBONE NETWORK COSTS*

	VDR = 2.4 Kbps	VDR = 8 Kbps	VDR = 16 Kbps	VDR = 64 Kbps
TRADITIONAL CIRCUIT SWITCHING	7.3 $M/mo	16.0 $M/mo	27.0 $M/mo	77.2 $M/mo
FAST CIRCUIT SWITCHING	3.3 $M/mo	4.8 $M/mo	6.6 $M/mo	14.7 $M/mo
HYBRID SWITCHING	2.5 $M/mo	3.0 $M/mo	3.5 $M/mo	6.3 $M/mo
PACKET SWITCHING	1.6 $M/mo	1.9 $M/mo	2.3 $M/mo	4.2 $M/mo

*Cost of voice digitization devices is not included.

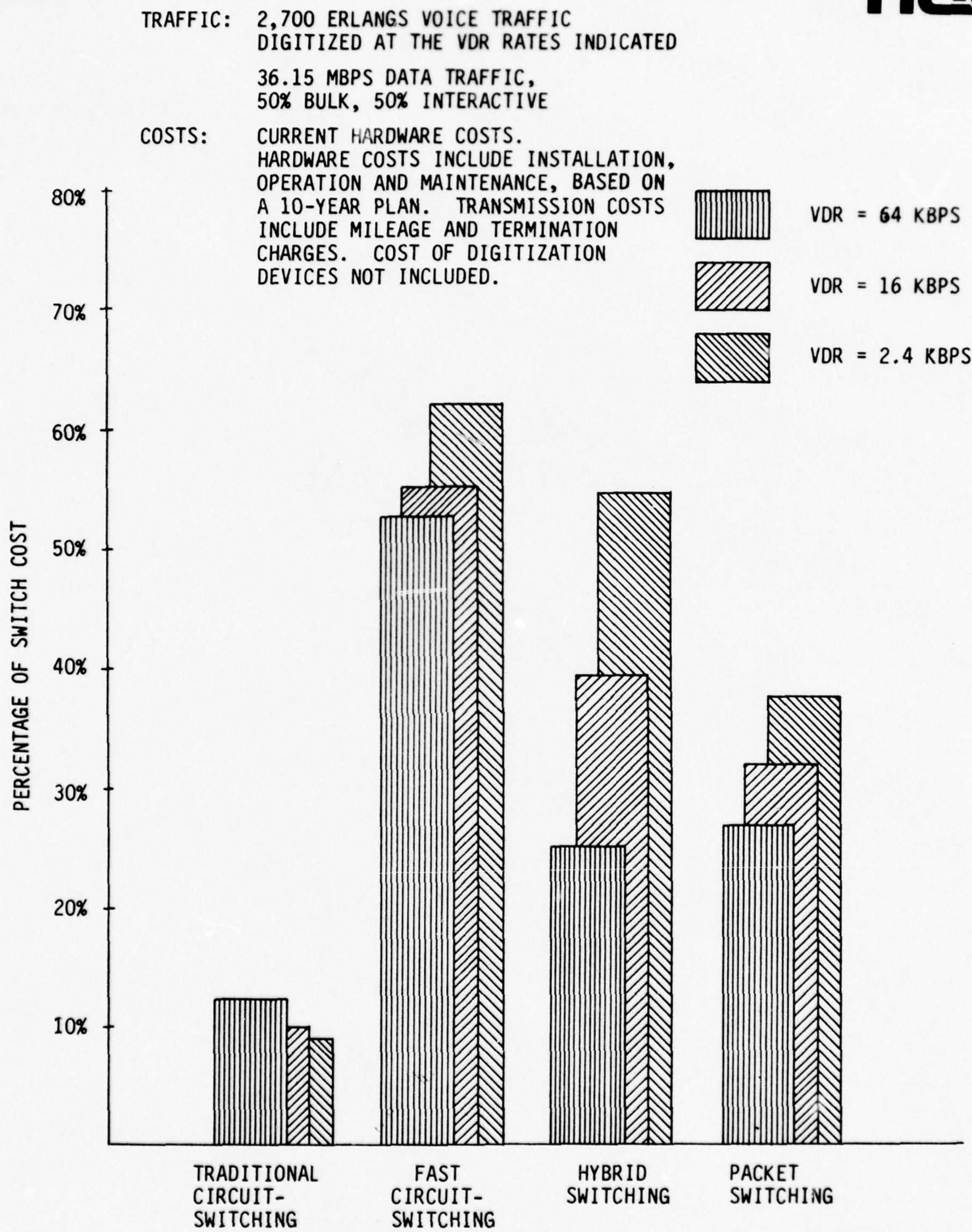


FIGURE 3.2: COMPARISON OF SWITCHING TECHNOLOGIES: SWITCH COMPONENT COST IN BACKBONE NETWORK COST

switching is characterized by the largest switching cost component. The latter results because of the large amount of processing required to set up and disconnect an end-to-end circuit for every data message of an interactive user. The second observation is that traditional circuit switching is the only technology where the percentage of switching cost increases with VDR. This indicates that the rate of growth of switching cost is higher than that of transmission cost for the range of VDR considered. As indicated before, the switching cost increases with an increase in transmission cost because of the channel interface and character transfer rate components in the switch cost model.

The sensitivity of the switch cost component to variations in VDR is smaller in the circuit-switching strategies than in hybrid switching or packet switching. Specifically, the percentage of switching cost over the VDR range considered varies between:

9% - 13% for traditional circuit switching,

53% - 62% for fast circuit switching,

25% - 55% for hybrid switching, and

27% - 38% for packet switching.

3.2.6 Discussion

The results and conclusions of Section 3.2.4 are the major results of the study. The understanding of these results is important in order to enable comprehension of the results of the studies that follow. Since the results may initially appear counter-intuitive, an explanation follows.

Two natural questions can be posed relative to the results shown in Figure 3.1. The first question concerns the relatively slow rate of cost increase more of the packet and hybrid-switching technologies compared to the relatively high rate of cost increase of the traditional circuit-switching technology as the voice digitization rate increases. The second question relates to the divergence between the cost curves of the traditional circuit-switching technology and the fast circuit-switching technology as voice digitization rate increases.

First, it is noted that the rate of increase in all switching technologies is much smaller than the rate of increase in the voice digitization rate. Even for traditional circuit

switching, the cost at VDR = 64 Kbps is only 10.6 times the cost at VDR = 2.4 Kbps, whereas the ratio in VDR values is 26.7. There are three reasons for the smaller rate of cost increase than that of the VDR ratio: economies of scale in the purchase of transmission facilities which result from the assumed tariff structure (based on DDS), the fact that voice is only part of the network traffic, and the fact that transmission is only part of the total cost. As VDR increases, costs for packet and hybrid switching increase more slowly than those of traditional circuit switching because the cost of packet and hybrid switches constitutes a higher fraction of the cost and because these technologies make a better utilization of the higher speed transmission facilities.

The relatively high rate of cost increase for the traditional circuit-switching technology and consequently the divergence from the fast circuit-switching curve observed in Figure 3.1 results primarily from the inefficiency of traditional circuit switching in handling interactive data applications. Recall that an interactive data user has, for the duration of the interactive session, an end-to-end channel at a bit rate equal to the voice digitization rate. Hence, when VDR is increased, channel utilization for traditional circuit switching by interactive data application decreases because transmission time of an interactive message decreases, but the time gap between interactive messages remains constant. Thus, the increase in VDR not only penalizes the voice users but also significantly reduces the efficiency of interactive data applications.

As voice digitization increases to 64 Kbps, the fraction of digital voice traffic becomes large (83%). However, even though voice traffic constitutes a high percentage in bits per second, it constitutes a small (constant and independent of VDR) percentage of the total traffic in terms of Erlang load offered to the system. Thus, even though the digital mix of voice and data is varying, the loads offered to the system under the conditions of Figure 3.1 are constant. The relative efficiency of the alternative network technologies for varying voice and data traffic loads are examined in the next section. In particular, the inefficiency of traditional circuit switching for varying loads is established as well as additional support and rationale for the results shown in Figure 3.1.

Finally, we explain the reason for the higher rate of cost increase of the fast circuit-switching technology as compared to hybrid switching and packet switching. For fast circuit switching, no channel capacity is dedicated to interactive users during idle periods and voice traffic is served in the same manner as in hybrid switching. However, for this technology, the higher rate of cost increase as a function of VDR results from the channel capacity wasted during circuit setup and disconnection. The model for circuit setup and

disconnection assumes that an end-to-end circuit is reserved link by link and that a reserved link capacity cannot be used by other traffic. Hence, such capacity is idle during the end-to-end circuit setup and disconnection. The holding time for the transmission of an interactive message is relatively small and decreases with an increase in VDR. On the other hand, the idle channel capacity increases with VDR because a circuit at the VDR value is being set up. Hence, although the number of circuit setups and disconnections is constant, the wasted capacity increases with VDR. Note also that the higher rate of cost increase of fast circuit switching results primarily from serving the interactive data applications but that higher link capacities also increase switch cost because of higher channel interface costs.

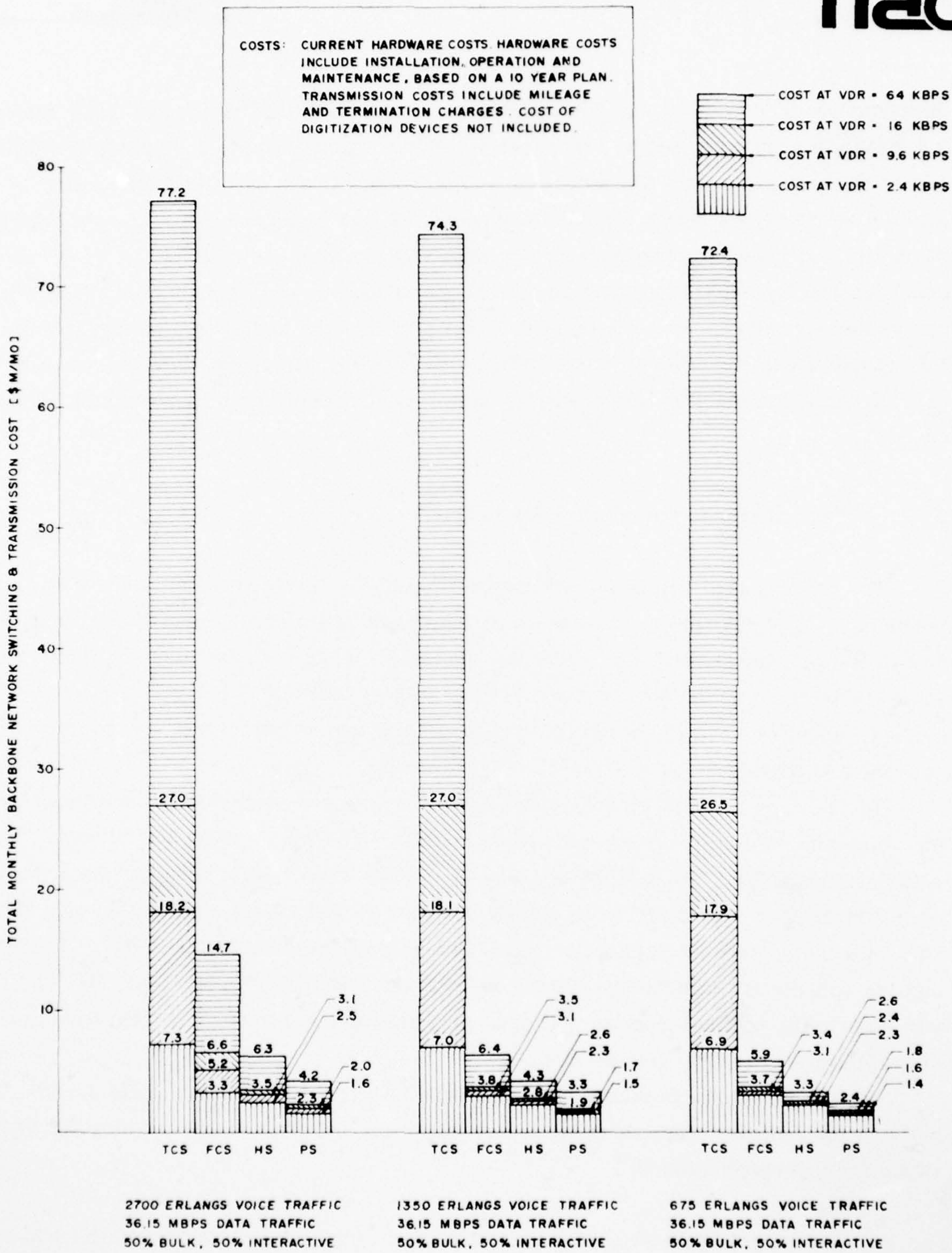
3.2.7 Sensitivity to Variations in Voice Traffic

The previous section has shown that the relationship between the alternative switching technologies is highly sensitive to the voice digitization rate parameter. In particular, the cost of the traditional switching technology increases rapidly with the voice digitization rate while the increase in the cost of the packet-switching technology is relatively small. This section compares network costs for different volumes of voice traffic and determines network cost sensitivity to variations in this parameter.

To facilitate the cost comparison, the alternative network technologies were designed for voice and data applications with voice loads of 675 Erlangs and 1350 Erlangs. These values correspond to 25% and 50% of the AUTOVON voice traffic used for the previously discussed designs. The data traffic is kept constant at 36.15 Mbps with the composition of 50% bulk data transfer applications and 50% interactive data applications. The voice digitization rate is varied to investigate the compound effect of voice Erlang load and VDR variations. The nominal blocking and delay performance requirements and the current price of switching and transmission are used.

Figure 3.3 shows backbone network switching and transmission costs for the four network technologies under three voice load scenarios and four values of voice digitization rate. The main conclusion is:

- *The ranking of switching technologies remains the same under variations in voice Erlang load, with packet switching the least costly and traditional circuit switching the most costly.*



MONTHLY BACKBONE SWITCHING AND TRANSMISSION COST AS A FUNCTION OF VOICE DIGITIZATION RATE (VDR), TRAFFIC SCENARIO AND SWITCHING TECHNOLOGY (TCS - TRADITIONAL CIRCUIT SWITCHING; FCS - FAST CIRCUIT SWITCHING; HS - HYBRID SWITCHING; PS - PACKET SWITCHING).

FIGURE 3.3

The analysis of cost shown in Figure 3.3 provides insight into the efficiency of handling voice and data by the alternative network technologies. When the voice load is reduced form 2,700 Erlangs to 675 Erlangs, the costs of packet switching, hybrid switching, and fast circuit switching decreases as one could have anticipated. On the other hand, the cost reduction of the traditional circuit-switching technology is smaller than what might be expected. A detailed examination of the operation of traditional circuit switching (as described in Chapter 2) and of the voice-data traffic mix, demonstrates that the small cost reduction results from the inefficiency of traditional circuit switching in handling interactive data applications. It is important to distinguish between the voice-data traffic mix in terms of bits per second on the one hand and in terms of Erlangs on the other hand. Voice traffic constitutes a high traffic fraction of total traffic in terms of bits per second, particularly at high voice digitization rates. However, when the data traffic is converted to Erlangs for transmission via a circuit-switching network, the data load constitutes the majority of the total traffic volume and thus a relatively large reduction in the voice traffic reduces the Erlang load only slightly. Traditional circuit-switching inefficiency results from the dedication of end-to-end circuits to interactive users for the duration of a session, thus inefficiently using transmission capacity during the idle periods. Note from Figure 3.3 that the total cost of traditional circuit switching decreases by at most 6.2% when the voice offered load decreases from 2700 Erlangs to 675 Erlangs, and the voice digitization rate is varied from 2.4 Kbps to 64 Kbps. For further corroboration, one can examine the costs of the hybrid-switching and fast circuit-switching technologies. These network technologies use a circuit-switching concept for voice communications and corresponding subnetworks are designed on the basis of the Erlang voice load, similar to the design of a traditional circuit-switching network; however, data traffic is handled more efficiently.

Quantitative results for the alternative network technologies over the range of voice and data traffic scenarios and voice digitization rates considered (see Figure 3.3) are:

- *Hybrid switching for voice and data is more costly than packet switching by 30%-64%.*

- *Fast circuit switching for voice and data is more costly than packet switching by 94%-250%.*

- *Traditional circuit switching is more costly than packet switching by 356%-2916%.*

The fact that traditional circuit switching carrying both voice and data traffic has such poor cost-performance characteristics compared to the other alternatives discussed should now be obvious. Traditional circuit switching performance extraordinarily poorly with respect to data traffic less than a few thousand bits. Moreover, all forms of circuit switching which do not detect and eliminate silences from speech have a substantial disadvantage with respect to line utilization over systems with silence detection. For example, in several cases packet and traditional circuit-switched systems carrying only voice traffic were examined. For these cases, costs ranged from approximately equal at very low rates of digitization to circuit switching costing about 38% more than packet switching at high digitization rates. As data traffic is then added, the performance of traditional circuit switching rapidly deteriorates.

3.2.8 Unit Cost Comparison of Alternative Network Technologies

This section compares the network technologies in terms of backbone network switching and transmission cost per Megabit of traffic. The cost per Megabit is equivalent to the cost per kilo-packet, assuming 1000 bit packets. This cost is often used to examine economy of scale as a function of traffic load [NETWORK ANALYSIS CORPORATION, 1977] or to examine switching and transmission cost trends. The comparison is provided as a function of voice digitization rate.

The unit costs presented in this section are not directly comparable with previous results (e.g., [NETWORK ANALYSIS CORPORATION, 1977],[MCAULAY, 1977]) because of additional factors taken into account in this study which include mix of voice and data traffic, voice digitization rate, and the different switching technologies. The reader should proceed with caution in attempting to compare the unit costs presented with prior published results, and pay careful attention to the underlying assumptions given below.

The traffic scenario used for the comparison includes: 2,700 Erlangs voice traffic and 36.15 Mbps data traffic. The total backbone switching and transmission costs used to derive the units costs are those shown in Figure 3.3 as obtained from current prices of switching and transmission. As in [MCAULAY, 1977] it is assumed that the network operates eight hours each working day, 173 hours per month. Increases in the operating time proportionally decrease the unit costs reported below.

Table 3.2 gives the unit costs of backbone switching and transmission per Megabit of traffic. From the tables over the voice digitization range 2.4 Kbps - 64 Kbps the unit cost ranges per Megabit are:

3.2¢ - 6.0¢	for packet switching
4.8¢ - 9.4¢	for hybrid switching
11.2¢ - 13.5¢	for fast circuit switching
27.5¢ - 58.8¢	for traditional circuit switching.

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TABLE 3.2: UNIT COST OF ALTERNATIVE NETWORK TECHNOLOGIES

VOICE DIGITIZATION RATE (KBPS)	COST OF BACKBONE SWITCHING AND TRANSMISSION PER MILLION BITS (IN CENTS) NETWORK TECHNOLOGY			
	PS	HS	FCS	TCS
2.4	6.0	9.4	12.4	27.5
9.6	5.2	8.0	13.5	47.1
16.0	4.7	7.1	13.4	54.6
64.0	3.2	4.8	11.2	58.8

TRAFFIC SCENARIO: 2,700 ERLANGS VOICE AND 36.15 MBPS DATA

CURRENT PRICE OF SWITCHING AND TRANSMISSION

PS-PACKET SWITCHING, HS-HYBRID SWITCHING, FCS-FAST CIRCUIT SWITCHING, TCS-TRADITIONAL CIRCUIT SWITCHING

3.3 SENSITIVITY OF COMPARISON OF SWITCHING TECHNOLOGIES TO SWITCHING AND TRANSMISSION COST PARAMETERS

The analysis of the switching and transmission cost components, in an optimum design, demonstrates that some switching technologies require substantially more transmission cost than switching cost while others reverse this relationship. Furthermore, the switching or transmission cost components vary as a function of the voice digitization rate. Hence, to obtain confidence in the conclusions resulting from the comparison of switching technologies under nominal (current) switching and transmission cost parameters, it is mandatory to examine whether the conclusions remain valid if the price of switching and transmission varies, since future switching and transmission cost trends will result in cost relationships markedly different from those existing today.

To investigate this problem, integrated voice and data networks are redesigned under all switching technologies assuming different trends in the price of switching and transmission. Apart from current prices, the technologies are investigated under the following two cost scenarios:

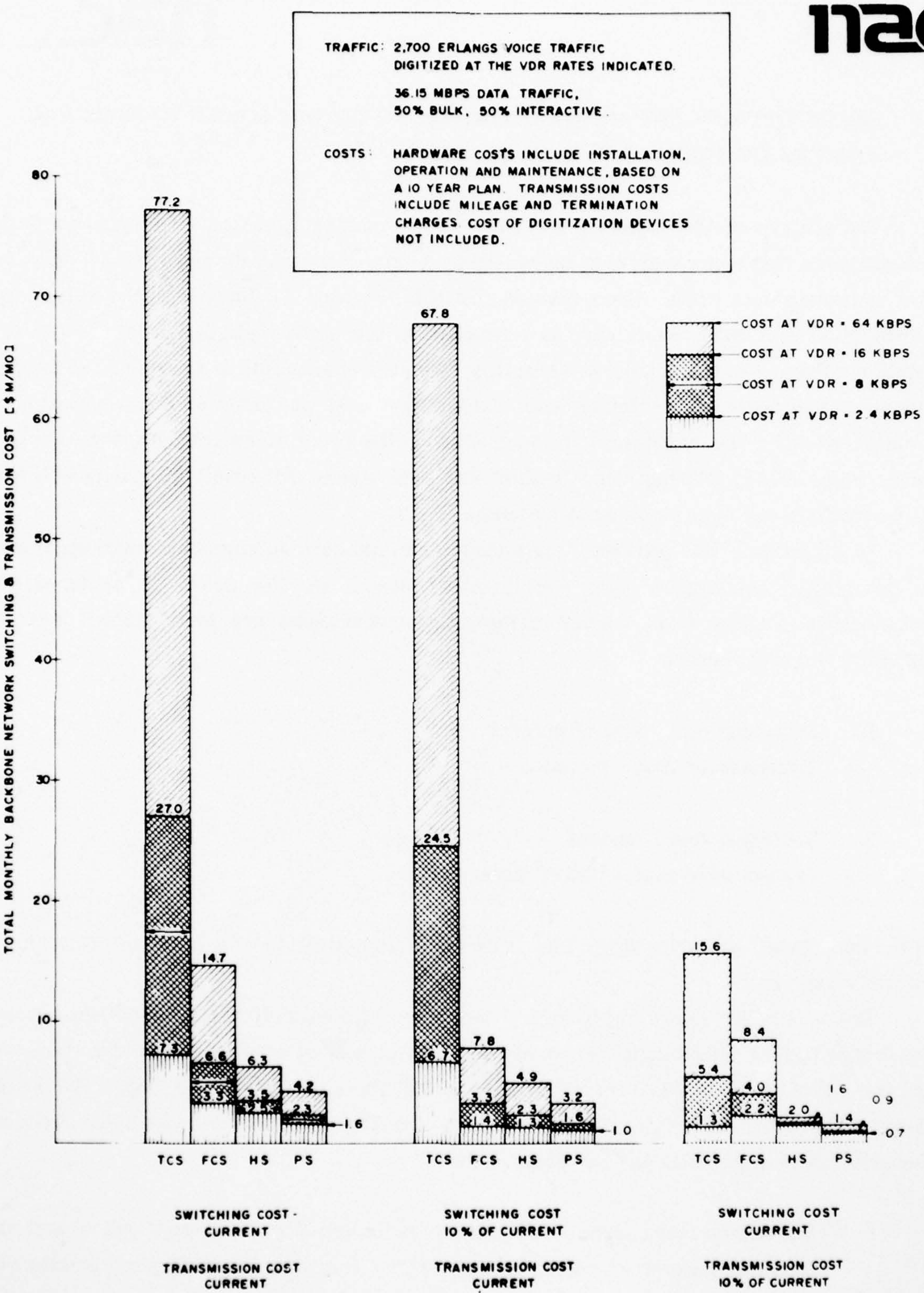
1. Switching cost - 10% of current
   Transmission cost - current.

2. Switching cost - current
   Transmission cost - 10% of current.

Note that these scenarios span two orders of magnitude in the ratio of switching to transmission cost.

The results are shown in Figure 3.4 where the total monthly backbone network costs of the four switching technologies are shown under three sets of assumptions (the current costs and the above two scenarios) for VDR values of 2.4 Kbps, 16 Kbps and 64 Kbps. The costs of backbone networks for a voice digitization rate of 8 Kbps are also shown for the current cost scenario. From Figure 3.4 one can observe that:

- *The major conclusion that packet switching for integrated voice and data provides lower-cost networks than any of the other technologies remains valid over the entire range of cost scenarios and voice digitization rates considered.*



MONTHLY BACKBONE SWITCHING AND TRANSMISSION COST AS A FUNCTION OF VOICE DIGITIZATION RATE (VDR), COMPONENT COST, AND SWITCHING TECHNOLOGY (TCS - TRADITIONAL CIRCUIT SWITCHING, FCS - FAST CIRCUIT SWITCHING, HS - HYBRID SWITCHING; PS - PACKET SWITCHING)

FIGURE 3.4

The ranking of the four switching technologies under scenario (1) where the price of switching is 10% of the current price remains the same as under the current price of switching and transmission. However, the fast circuit-switching technology, which heavily relies on switching, is nearly as cost-effective as the hybrid-switching technology, particularly at low VDR values. This results directly from the reduction in switching cost and the fact that the complexity of a circuit switch is much lower than that of a hybrid switch.

The ranking of switching technologies also changes under cost scenario (2) where the price of transmission is 10% of the current price. Traditional circuit switching costs less than fast circuit switching and hybrid switching for VDR = 2.4 Kbps. However the cost difference between traditional circuit switching and hybrid switching is less than 8%.

To investigate the cost-effectiveness of the packet-switching technology, the ratios of total backbone network costs of other switching technologies to the packet-switching technology are tabulated in Table 3.3. From Table 3.3 it is concluded that, over the entire range of cost scenarios and VDR values:

- *Hybrid switching for voice and data is more costly than packet switching by 30% - 100%.*

- *Fast circuit switching for voice and data is more costly than packet switching by 40% - 500%.*

- *Traditional circuit switching for voice and data is more costly than packet switching by 90% - 1740%.*

TABLE 3.3: BACKBONE COST RATIOS OF SWITCHING TECHNOLOGIES TO THE PACKET SWITCHING TECHNOLOGY (COST OF VOICE DIGITIZATION DEVICES ARE NOT INCLUDED)

	SWITCHING COST - CURRENT TRANSMISSION COST - CURRENT				SWITCHING COST - 10% OF CURRENT TRANSMISSION COST - CURRENT			SWITCHING COST - CURRENT TRANSMISSION COST - 10% OF CURRENT		
	VDR=2.4 KBPS	VDR=8 KBPS	VDR=16 KBPS	VDR=64 KBPS	VDR=2.4 KBPS	VDR=16 KBPS	VDR=64 KBPS	VDR=2.4 KBPS	VDR=16 KBPS	VDR=64 KBPS
TCS/PS	4.6	8.4	11.7	18.4	6.7	15.3	21.2	1.9	6.0	11.1
FCS/PS	2.1	2.5	2.9	3.5	1.4	2.1	2.4	3.1	4.4	6.0
HS/PS	1.6	1.6	1.5	1.5	1.3	1.4	1.3	2.0	1.8	1.4

LEGEND:

TCS - TRADITIONAL CIRCUIT SWITCHING
FCS - FAST CIRCUIT SWITCHING
HS - HYBRID SWITCHING
PS - PACKET SWITCHING

3.4 INTEGRATED VS. SEGREGATED VOICE AND DATA NETWORKS

The objective of this section is to compare integrated versus segregated voice and data communications systems under the four switching technology as a function of voice digitization rate.

The interest in this comparison is twofold. First, separate voice and data networks using the same switching technology may be developed by DOD as part of the evolutionary plan for integrated communication systems. Second, it is of value to examine the cost differences between integrated and segregated systems since the cost differences will indicate the potential savings to be gained by fully integrated systems. Current prices of switching and transmission are used in these investigations. The cost for switching reflects the price of existing computer systems and the cost of transmission is modeled according to current DDS tariff offerings.

Figure 3.5 shows the total monthly cost of two separate voice and data networks and an integrated voice and data network for each switching technology as a function of VDR. The cost difference between separate networks and a common network does not demonstrate a consistent trend as a function of VDR. That is, for some switching technologies the cost difference increases as a function of VDR while for others it decreases. The only trend that can be observed from Figure 3.5 is that the percentage savings that could be obtained from integrated communications relates to the ranking of switching technologies with the highest percentage savings for packet switching and the lowest for traditional circuit switching. Specifically, the percentage cost increases in the separate network case as compared to an integrated voice and data network, for VDR between 2.4 Kbps and 64 Kbps, are:

1.2% - 6.4%	for traditional circuit switching,
3.3% - 10.2%	for fast circuit switching,
4.6% - 13.1%	for hybrid switching, and
17.1% - 21.7%	for packet switching.

The major conclusion from these investigations is that:

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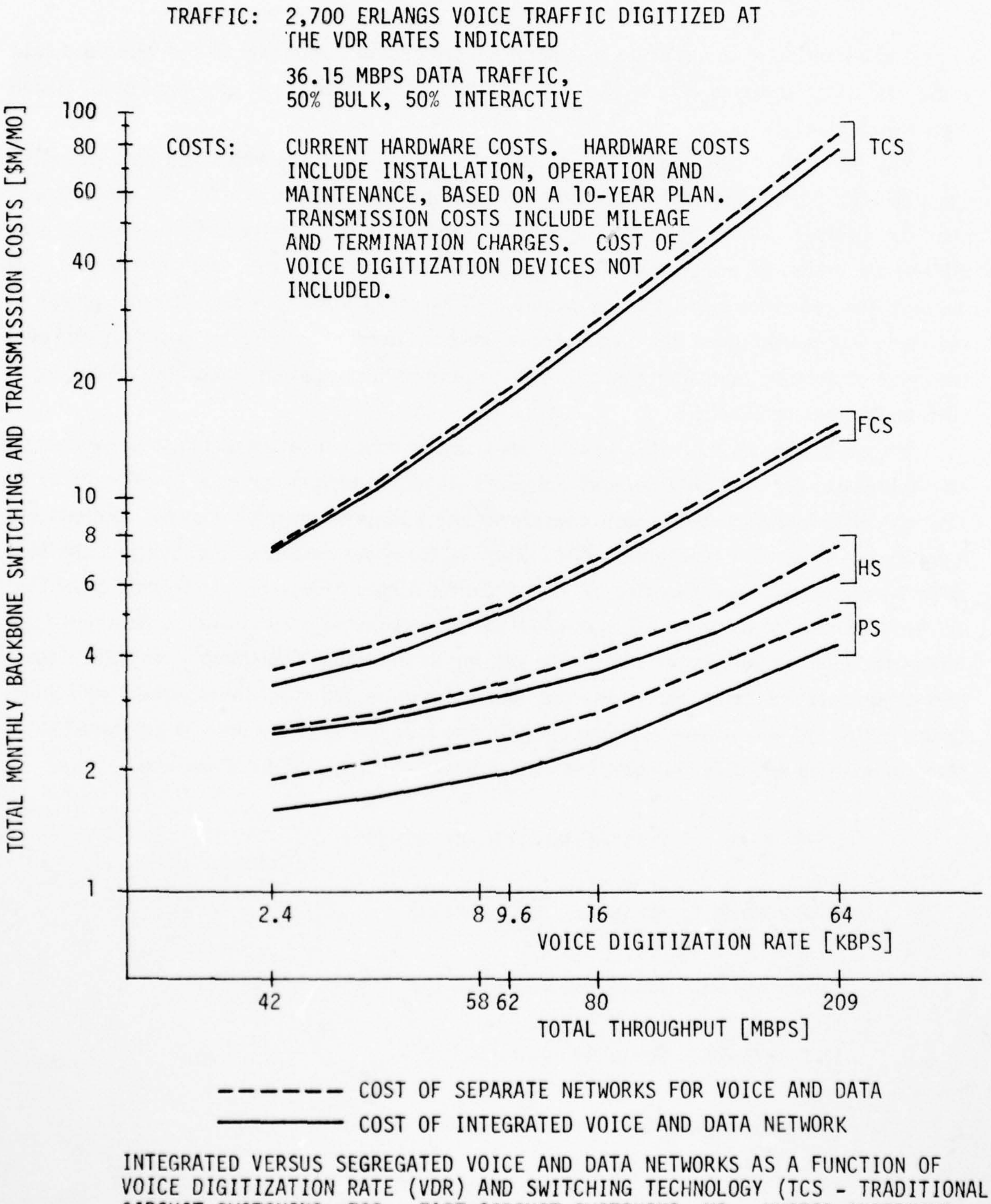

INTEGRATED VERSUS SEGREGATED VOICE AND DATA NETWORKS AS A FUNCTION OF VOICE DIGITIZATION RATE (VDR) AND SWITCHING TECHNOLOGY (TCS - TRADITIONAL CIRCUIT SWITCHING; FCS - FAST CIRCUIT SWITCHING; HS - HYBRID SWITCHING; PS - PACKET SWITCHING)

FIGURE 3.5

- *The backbone network cost of two separate packet-switching systems (one for voice and one for data) is lower than the cost of an integrated voice and data system under any of the alternative switching technologies, for the entire range of voice digitization rate.*

It is important to note that while the cost differences between segregated and integrated systems does not appear to be major, the costs calculated represent switching and transmission costs. Other costs, such as manning must be explicitly considered to fully trade off the costs of integrated versus segregated systems. Thus, while the DCA conversion method (see Section 2.3.2) for costing is a good first step in developing O&M costs for a system, it does not provide a mechanism for truly estimating the manning requirements between integrated and separate systems which is a major contributor to life cycle cost. For example, if a voice circuit switch and a data packet switch were identical in purchase cost to an integrated voice and data switch, the DCA cost manual would derive identical O&M costs. In reality these costs might be different. However, this problem was beyond the scope of the present effort and is raised here to highlight this area of uncertainty. Another point is that the major advantage of an integrated system may not be that it is substantially cheaper but that it provides significant flexibility "after a particular design is implemented" to match resources to changing mixes of traffic. For example, during crises conditions, operation under jamming, and/or damage to portions of the network, more users can be satisfied through data communications than through voice. An integrated system could shift resources gracefully to match these changes, while a separate system approach might be less flexible.

3.5 *NETWORK ECONOMICS WITH VOCODERS*

The analysis and cost comparison of switching technologies in the preceding sections examined the switching and transmission costs of the backbone network. The location of voice digitization devices and the cost of the digitization process were not taken into account. This is equivalent to assuming that voice is digitized prior to its processing in the backbone network.

The ranking of network technologies for the backbone is independent of the cost of digitization devices; however a total system cost comparison including the digitization cost will reduce the percentage difference between alternative strategies. The study of alternative locations for voice digitizers is important from both cost and security perspectives. It was demonstrated in previous sections that the switching and transmission costs of the backbone network increases with the voice digitization rate. Hence it is important to investigate the tradeoff between the cost of a low VDR backbone network plus the cost of digitizers to provide the low bit rate, against the cost of a network using high VDR such as PCM (Pulse Code Modulation) at 64 Kbps.

This section compares costs of the alternative network technologies including the cost of voice digitizers. The comparison is done under a variety of assumptions of digitization rate, location, and purchase price of voice digitizers. The following two problems are addressed:

Problem 1:

Cost-effectiveness of voice digitization devices (vocoders) in the backbone network: For this problem it is assumed that the voice subscriber operates in an analog environment. The question to be answered is whether it is cost-effective to provide low bit rate voice digitizers in the backbone network to reduce the total system cost (backbone network plus digitizers).

Problem 2:

Economics of voice digitization devices in handsets: The problem is to determine the total cost, including backbone network cost for a given VDR value and the cost of digitizers as a function of number of handsets.

Problem 1 is of interest where secure end-to-end digital voice is not a requirement. Hence, the emphasis is strictly on cost-effectiveness. In the DOD environment, a solution whereby the voice digitizers reside *only* in the backbone network may not be desirable if end-to-end encryption is sought. In this case a question to be posed is: for a specified total budget, what is the number of handsets which can be equipped with digitizers, of say 2.4 Kbps, under the various switching technologies.

To address Problem 2, when voice is digitized at the handset, it is necessary to take into account the savings in the local distribution network which results from the low bit rate voice. Detailed costing of local distribution networks is not examined in this study. Previous studies [NETWORK ANALYSIS CORPORATION, 1977], [NETWORK ANALYSIS CORPORATION, 1975] have shown that the communications cost of local distribution networks (communication channels, multiplexing, concentration) is on the order of 50% of the total system cost. Hence, the quantitative results under the handset digitization option are derived under the assumption that the communications cost of the local distribution system is equal to the communications cost of the backbone network (switching and transmission) for each of the network technologies compared.

A digitization strategy whereby some voice requirements are digitized at the handset and others at the backbone network (combination of Problems 1 and 2) is also addressed. This option is attractive when the number of voice subscribers requiring end-to-end encryption is small compared to the total number of subscribers using the network. In such a case voice digitizers can be provided in the backbone network to reduce total system cost; these digitizers are shared by subscribers with analog local loops. Furthermore, this mixed digitization strategy could be cost-effective as an interim step in the evolution of DOD communications to an all digital system.

It is noted that the differences in the cost for terminals with vocoders where packetization is required, as opposed to those working in a circuit-switched environment were not evaluated. The components of processing for a packet voice system are discussed in Section 2.1.3.2 and Sections A.5 and A.6 of the Appendix. If packetizing is performed at the terminal, the terminal will be required to collect vocoded digital speech windows and package and address them to form a packet. Depending on the protocol used, windows from one to several terminals might be placed into a single packet. In the latter case, this process might occur in a device intermediate to the terminal and backbone switch such as a telephone branch exchange located within the building. Additionally, either this device or the terminal would contain the adaptive delay buffer discussed in Section 2.1.3.2. In any event, these packetizing functions have become straightforward and are expected to have a small cost compared to the cost of the vocoder.

3.5.1 Voice Digitization in the Backbone Network

The model for providing digitization devices in the backbone network is shown in Figure 3.6. A bank of digitization devices is provided at each switching node. As shown, digitization devices at the origination and destination switches are dedicated to the pair engaged in conversation for the duration of the call. No additional digitization devices are used by the pair in tandem (intermediate) switches. The bank of digitizers is dynamically shared rather than permanently dedicated to subscribers, in order to minimize the number of such devices required to achieve the low bit rate backbone network.

The maximum number of digitizers needed in the backbone network for the voice traffic is 15,912. This allows the maximum number of voice connections in the network for the given Erlang traffic. That is, for every point-to-point "circuit" needed to accommodate voice communication, a digitizer is provided at both ends. The above number was assumed for all switching technologies in the results that follow. However, this number can be reduced by providing a smaller number than the maximum (of voice digitizers in backbone nodes), resulting in the possibility of subscriber rejection by the system because of unavailability of digitizers. The rejection event should be made rare, for example, less than .2%.

Figures 3.7 and 3.8 show the total cost of the backbone network plus the cost of all digitizers needed in the backbone network for all switching technologies, for the 2.4 Kbps and 16 Kbps cases, respectively, as a function of the purchase price of a digitizer. The cost of the networks with VDR = 64 Kbps (PCM) are also shown. The cost of networks with VDR = 64 Kbps is nearly constant since these devices are very inexpensive. These so-called codecs are available from several manufacturers at a price below $5 per subscriber [FALK, 1977] .

It is interesting to observe the price of digitizers below which the cost of the low bit rate network plus the cost of the devices is lower than the cost of the network with VDR = 64 Kbps, for the same switching technology. This is the price range within which it is cost-effective to provide low bit rate voice digitizers in the backbone network.

It is apparent that when the switching and transmission costs of a particular technology increase rapidly with VDR, it would be economical to provide low bit rate voice digitizers in the backbone network at relatively high costs per device. For example, in Figure 3.7 one can see that for traditional circuit switching it is cost-effective to provide 2.4 Kbps VDR devices in the backbone network (rather than using PCM rate) when the

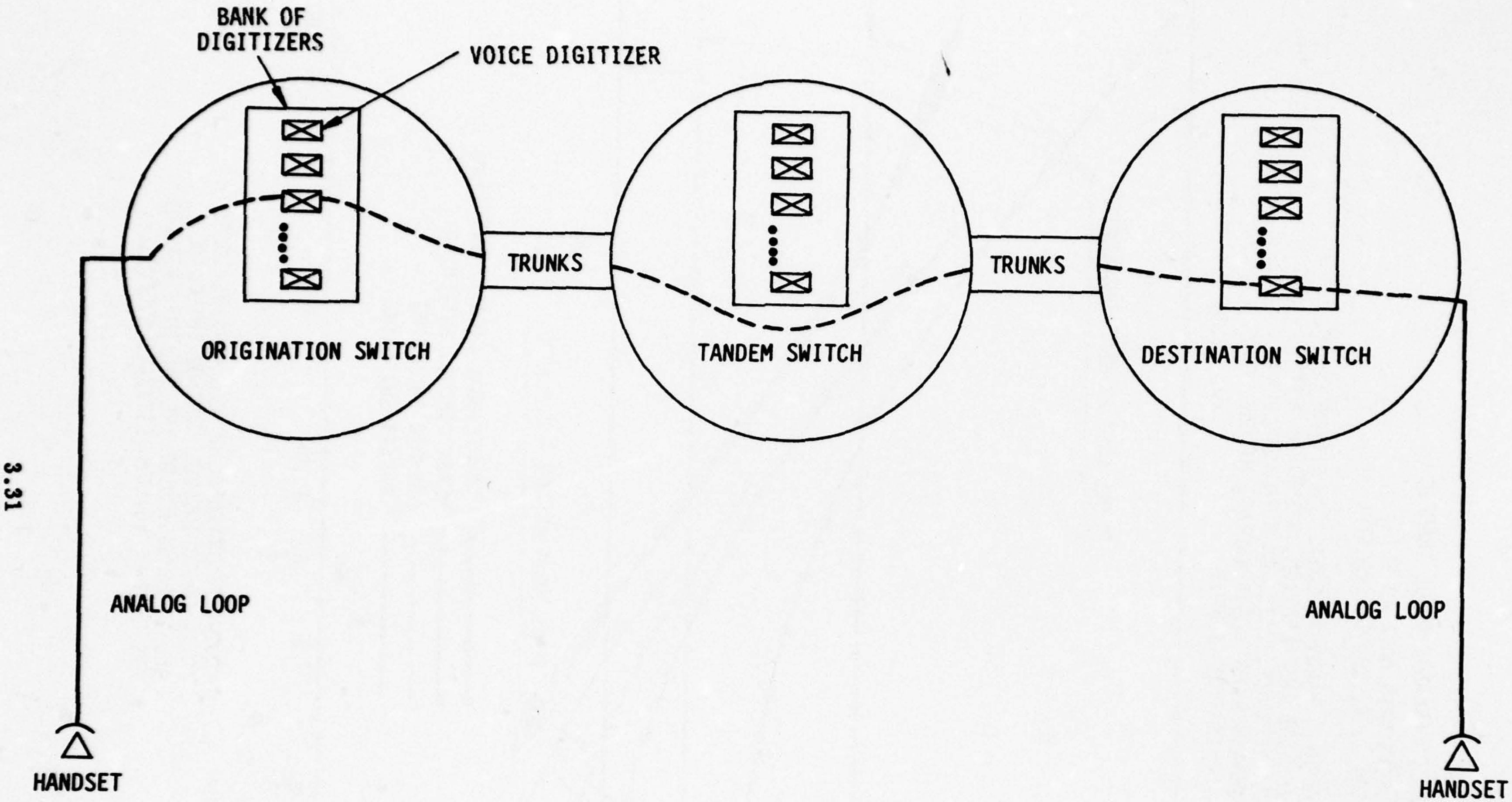

FIGURE 3.6: MODEL FOR PROVIDING VOICE DIGITIZERS IN BACKBONE NETWORK

![nac logo]

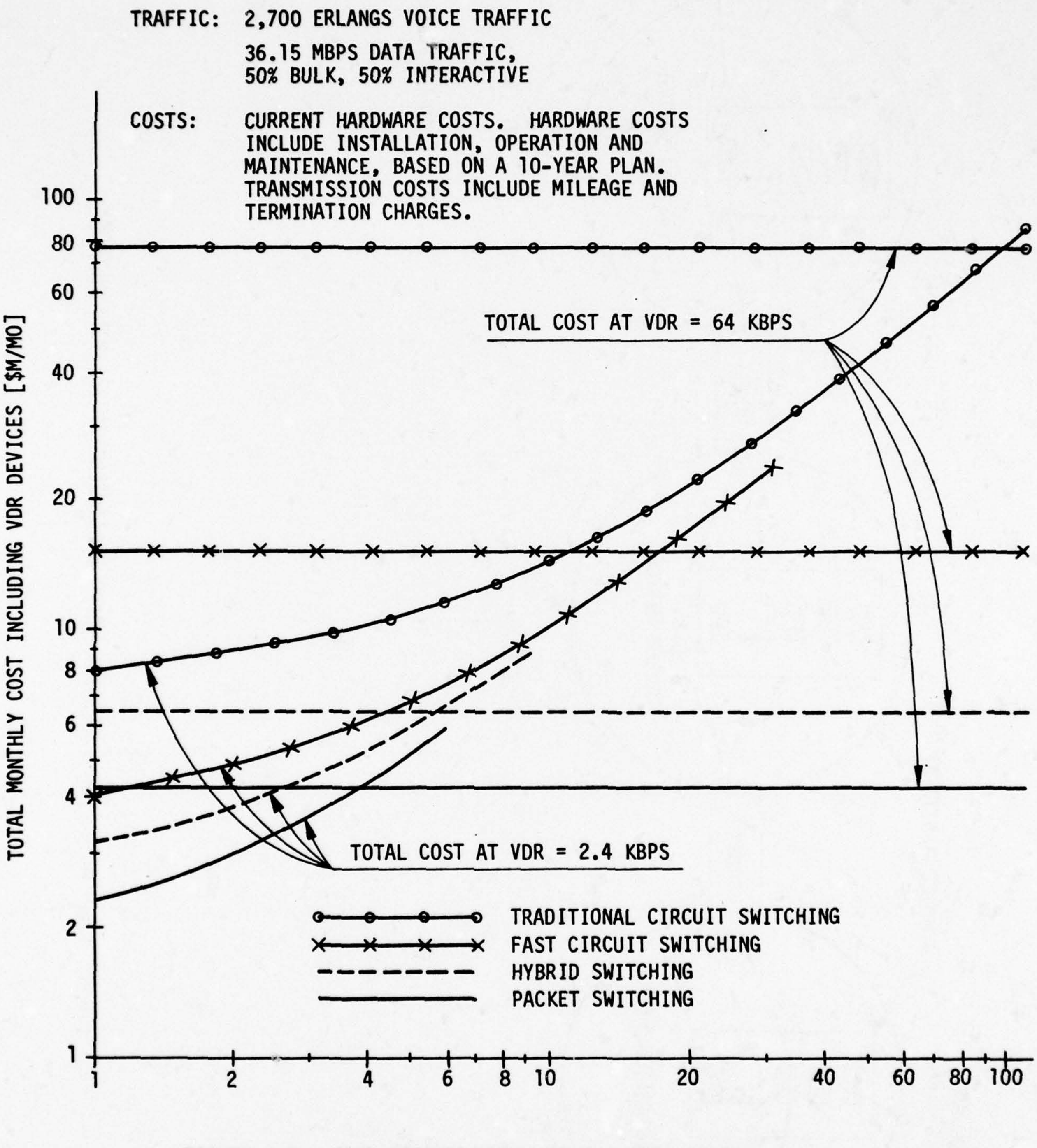

FIGURE 3.7: COST-EFFECTIVENESS OF 2.4 KBPS DEVICES: TOTAL COSTS INCLUDE COST OF SWITCHING AND TRANSMISSION OF THE BACKBONE NETWORK AND COST OF VOICE DIGITIZATION DEVICES

nac

TRAFFIC: 2,700 ERLANGS VOICE TRAFFIC
36.15 MBPS DATA TRAFFIC,
50% BULK, 50% INTERACTIVE

COSTS: CURRENT HARDWARE COSTS.
HARDWARE COSTS INCLUDE INSTALLATION, OPERATION AND MAINTENANCE, BASED ON A 10-YEAR PLAN. TRANSMISSION COSTS INCLUDE MILEAGE AND TERMINATION CHARGES.

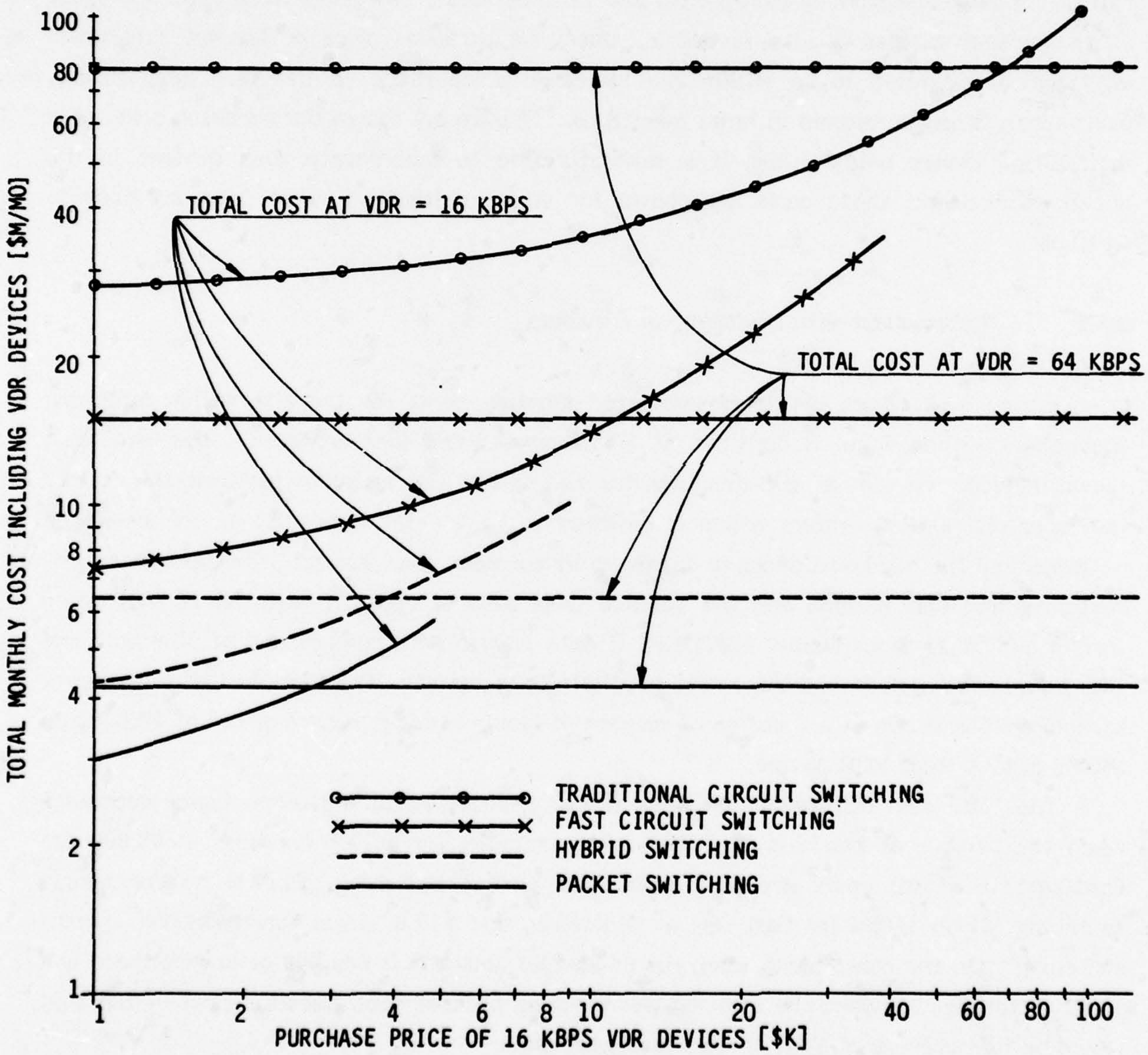

FIGURE 3.8: COST-EFFECTIVENESS OF 16 KBPS VOICE DIGITIZERS: TOTAL COSTS INCLUDE COST OF SWITCHING AND TRANSMISSION OF THE BACKBONE NETWORK AND COST OF VOICE DIGITIZATION DEVICES

purchase price of such a device is below $98,000. Table 3.4 summarizes the break-even points of the purchase price per voice digitizer below which it is cost-effective to provide these devices in the backbone network.

From Table 3.4 one can conclude that with currently quoted prices for voice digitizers, circuit-switched networks should be engineered with low bit rate digitizers in backbone switches. Alternatively, given a digital switching and transmission system for voice at PCM rates, it is cost-effective to incorporate low VDR devices. The break-even point for other switching technologies is also favorable, since the purchase price of low bit rate voice digitizers is expected to be within the indicated price range in the very near future, particularly when purchased in large quantities. Figure 3.9 shows the purchase price of a digitization device below which it is cost-effective to incorporate such devices in the backbone network; these costs are shown for voice digitization rates from 2.4 Kbps to 64 Kbps.

3.5.2 System Cost with Digitizers in Handsets

Figure 3.10 shows the total estimated monthly costs for the alternative switching technologies when voice is digitized at 2.4 Kbps at subscriber handsets. The total cost shown includes the cost of switching and transmission of the backbone network, the cost of the local distribution system which is assumed to be the same as that of the backbone network, and the total cost of voice digitizers in handsets. The current price parameters for switching and transmission and the nominal data base of 2,700 Erlangs AUTOVON voice traffic and 36.15 Mbps scaled AUTODIN II data traffic with composition of 50% bulk and 50% interactive applications were used to obtain these results. The total cost of all network technologies is shown as a function of number of handsets for purchase prices of $2,000 and $5,000 per 2.4 Kbps VDR device.

The total cost differences between the alternative switching technologies decreases when the number of handsets increases. For example, for 50,000 handsets at $2,000 per digitizer, the total costs are $7.6 M/mo for packet switching, $9.4 M/mo for hybrid switching, $11.0 M/mo for fast circuit switching, and $19.0 M/mo for traditional circuit switching. On the other hand, when the number of handsets is 600,000 or larger, there is a small difference between the alternative switching technologies, because most of the cost would be for purchase of VDR devices in the handsets.

nac

TABLE 3.4: COSTS BELOW WHICH IT IS ECONOMICAL TO PROVIDE VOICE DIGITIZERS IN THE BACKBONE NETWORK

	2.4 KBPS VDR DEVICE	16 KBPS VDR DEVICE
TRADITIONAL CIRCUIT SWITCHING	$98,000	$70,000
FAST CIRCUIT SWITCHING	$16,500	$11,500
HYBRID SWITCHING	$ 5,500	$ 3,900
PACKET SWITCHING	$ 3,700	$ 2,800

TRAFFIC: 2,700 ERLANGS VOICE TRAFFIC
36.15 MBPS DATA TRAFFIC,
50% BULK, 50% INTERACTIVE

COSTS: CURRENT HARDWARE COSTS.
HARDWARE COSTS INCLUDE INSTALLATION, OPERATION AND MAINTENANCE, BASED ON A 10-YEAR PLAN. TRANSMISSION COSTS INCLUDE MILEAGE AND TERMINATION CHARGES.

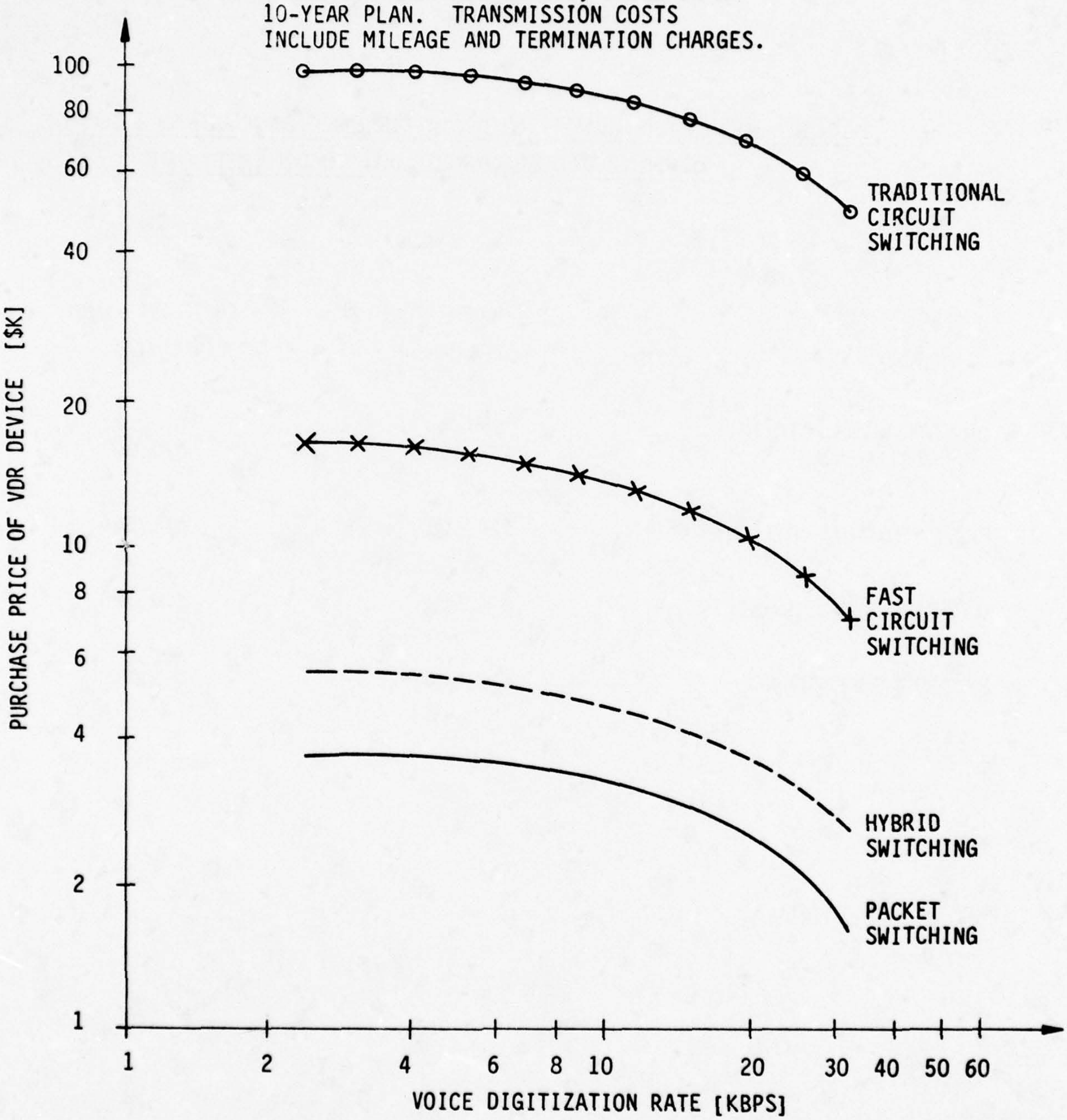

FIGURE 3.9: COST OF A DIGITIZATION DEVICE BELOW WHICH IT IS COST-EFFECTIVE FOR INCORPORATION INTO THE BACKBONE NETWORKS

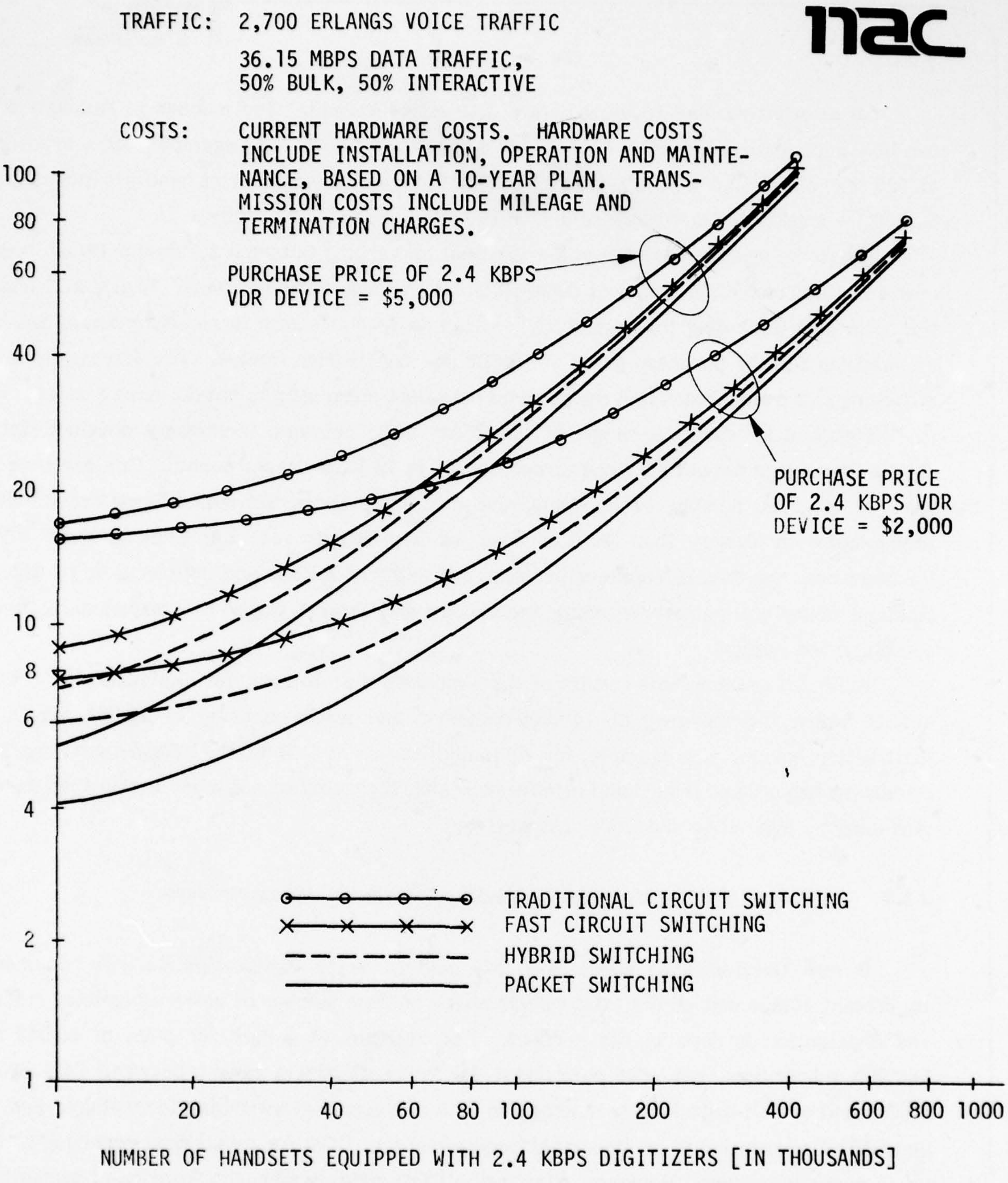

FIGURE 3.10: COMPARISON OF SWITCHING TECHNOLOGIES WITH VOICE DIGITIZATION AT THE SUBSCRIBER HANDSETS: TOTAL MONTHLY COST INCLUDES BACKBONE NETWORK, ESTIMATED COST OF THE LOCAL DISTRIBUTION SYSTEM, AND COST OF VOICE DIGITIZATION DEVICES.

An alternative way to view Figure 3.10 is to determine the number of handsets that can be equipped with low VDR devices for a given total cost. For example, for a total cost of $20 M/mo and $2,000 purchase price per VDR device, the number of handsets ranges from 60,000 for traditional circuit switching to 200,000 for packet switching.

The total system cost for voice digitization varying between 8,000 and 16,000 bps is now examined under the option of digitization at the subscriber handsets. Figure 3.11 shows the total cost (including the cost of digitization devices at handsets) as a function of number of handsets for the purchase price of $2,000 per digitization device. The current price of switching and transmission and the nominal data base were used to obtain these results.

Figure 3.11 shows a range of costs for each network technology obtained for a digitization range between 8 Kbps (lower bound) to 16 Kbps (upper bound). One can observe that for a given number of handsets, the cost differences between alternative network technologies is larger than in the case of digitization at 2.4 Kbps (Figure 3.10). Furthermore, the cost differences between digitizing at 8 Kbps and digitizing at 16 Kbps is smallest under the packet switching technology and largest under the traditional circuit-switching technology.

Table 3.5 gives sample results of total monthly system cost, for digitization at 8 Kbps and 16 Kbps, for the case of 100,000 handsets and purchase price of $2,000 per voice digitization device. For example, for voice digitization at 8 Kbps, the hybrid-switching, fast circuit-switching, and traditional circuit-switching technologies are more costly than packet switching by 17%, 46%, and 224%, respectively.

3.5.3 *Voice Digitization in the Handset and in the Backbone Network*

It was demonstrated above that the cost of voice digitization devices becomes a significant component of the total system cost when the number of voice subscribers is large and digitization is done at the handset. For example, at a digitizer price of $2,000 and 500,000 subscribers, the cost component for voice digitizers ranges between 74% in the traditional circuit-switching technology to 91% in the packet-switching technology. End-to-end digital encryption is an important requirement in DOD for subscribers requiring secure voice communications. However, even in the DOD environment, the fraction of subscribers requiring secure voice communications is expected to be small compared to the total number of voice subscribers in the DOD. For example, in [SIGNAL, 1977] it was quoted that a nominal expanded number of secure voice subscribers is 10,000. At present, secure voice

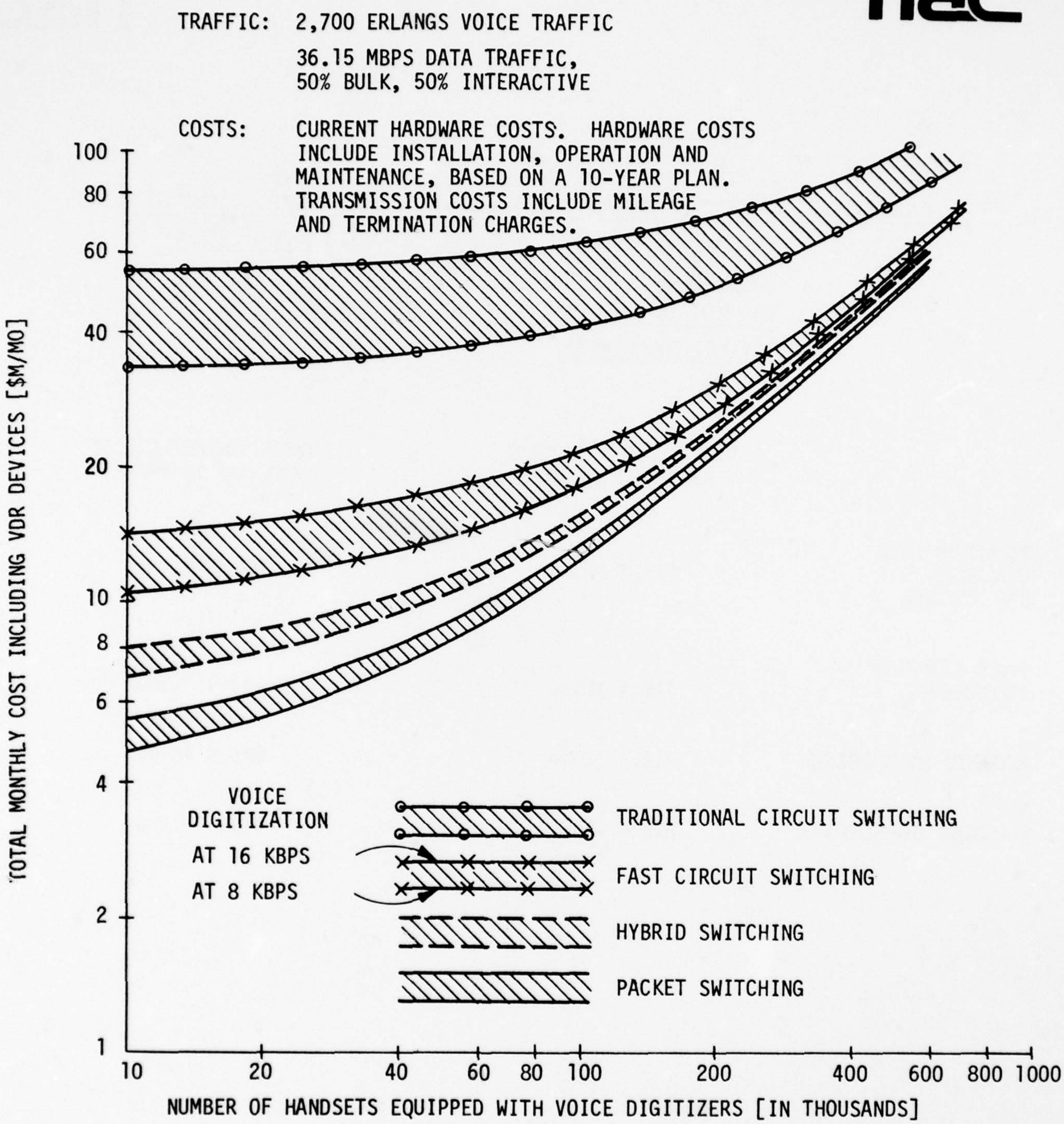

FIGURE 3.11: COMPARISON OF SWITCHING TECHNOLOGIES WITH VOICE DIGITIZATION AT SUBSCRIBER HANDSETS, FOR VOICE DIGITIZATION BETWEEN 8 KBPS AND 16 KBPS: TOTAL MONTHLY COSTS INCLUDE BACKBONE NETWORK, ESTIMATED COST OF VOICE DIGITIZATION DEVICE IN HANDSETS.

TABLE 3.5: SAMPLE RESULTS COMPARING TOTAL SYSTEM MONTHLY COST (BACKBONE NETWORK, LOCAL DISTRIBUTION NETWORK, VOICE DIGITIZATION DEVICES) FOR THE OPTION OF DIGITIZATION IN THE HANDSET FOR 100,000 HANDSETS

	VOICE DIGITIZATION RATE OF 8 KBPS	VOICE DIGITIZATION RATE OF 16 KBPS
TRADITIONAL CIRCUIT SWITCHING	$40.8 M/mo	$62.8 M/mo
FAST CIRCUIT SWITCHING	$18.4 M/mo	$22.0 M/mo
HYBRID SWITCHING	$14.8 M/mo	$15.8 M/mo
PACKET SWITCHING	$12.6 M/mo	$13.4 M/mo

communications is accommodated by the AUTOSEVOCOM whereas all other DOD voice subscribers use the AUTOVON switched network.

In previous sections it was demonstrated that it is cost-effective to digitize voice at the backbone network at anticipated prices for voice digitization devices. Hence, a digitization strategy whereby voice is digitized at the backbone switches for subscribers not requiring end-to-end digital encryption and digitized the handset for subscribers requiring secure voice communications appears to be a cost-effective approach for integrating secure and non-secure voice communications. The results under this strategy are reported below.

Figure 3.12 provides the cost comparison of alternative network technologies as a function of number of handsets equipped with voice digitization devices. The values shown in Figure 3.12 were obtained using the current price of switching and transmission, the nominal data base of 2,700 Erlangs and 36.15 Mbps data (50% bulk and 50% interactive), and a purchase price of $2,000 per voice digitization device. The costs are for switching and transmission in the backbone network, voice digitizers at the backbone switching nodes and voice digitizers at the secure subscriber handsets. The range of handsets with digitizers considered is from 1,000 to 70,000. This range is expected to include DOD requirements for subscribers requiring secure voice communications. For a given number of handsets, a range of cost is shown for each network technology; this cost range corresponds to the voice digitization bit rate range from 8 Kbps (lower value cost) to 16 Kbps (higher value cost). The cost of the local distribution system is not taken into account. Under the digitization strategy considered, local distribution can be analog based for all subscribers apart from those requiring end-to-end digital encryption. Hence, the cost of local distribution systems for all network technologies would be equal.

Figure 3.12 shows that the cost of the packet switching technology under the mixed digitization strategy is lower than the cost of alternative network technologies. For example, for a voice digitization rate of 8 Kbps and 10,000 subscribers requiring secure voice communications, the hybrid-switching, fast circuit-switching, and traditional circuit-switching technologies are more costly than the packet-switching technology by 27%, 71% and 360%, respectively.

A different way of comparing the alternative network technologies is to determine the number of digitization devices that can be supported under a given total budget for the communications system. Figure 3.13 shows the number of voice digitization devices that can be supported as a function of the purchase price per VDR device for a voice digitization rate of 8 Kbps. Two sets of curves are shown for total monthly budgets of $20 million and

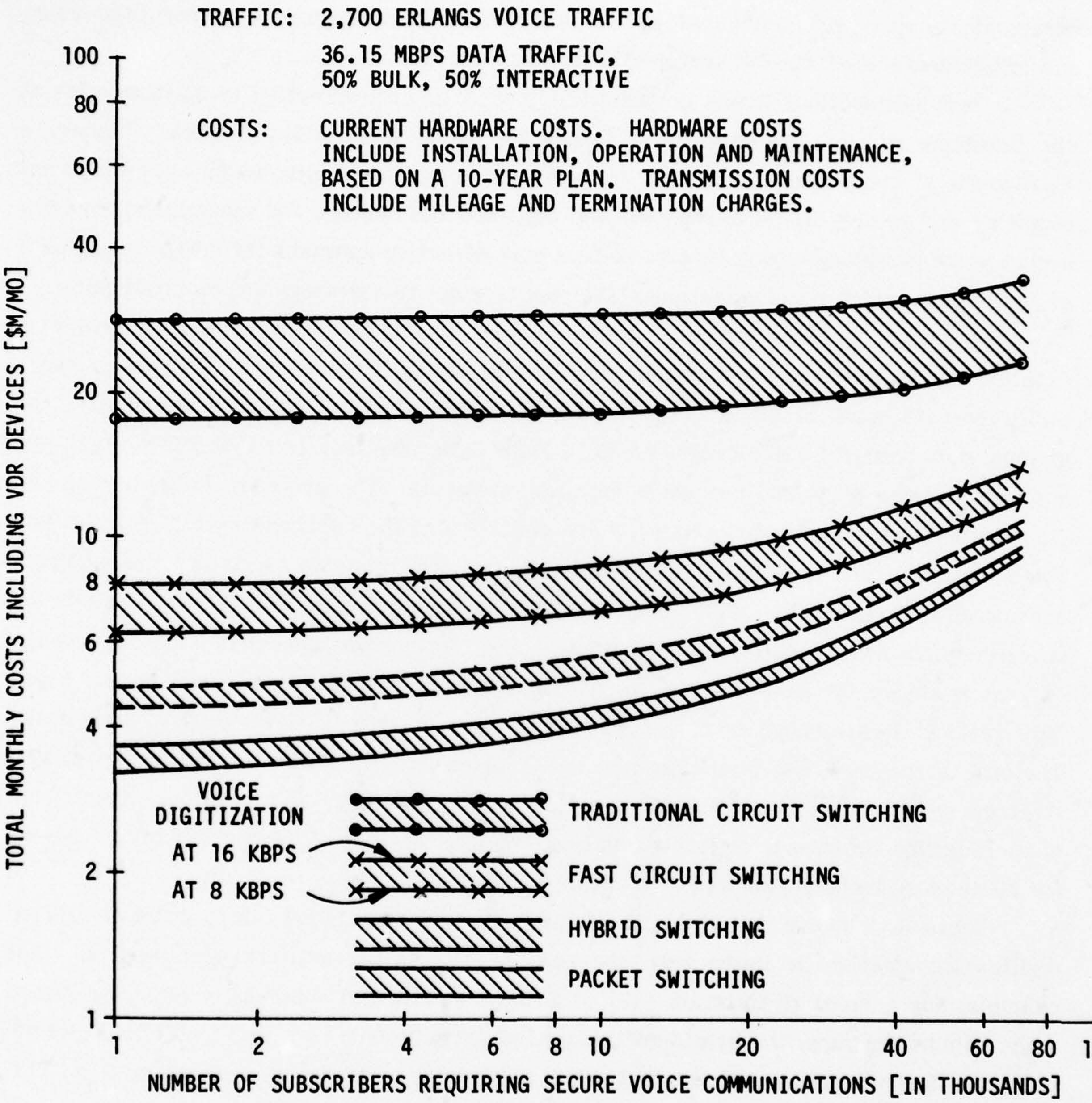

FIGURE 3.12: COMPARISON OF SWITCHING TECHNOLOGIES UNDER VOICE DIGITIZATION AT THE BACKBONE AND IN THE HANDSETS - AS A FUNCTION OF NUMBER OF SUBSCRIBERS REQUIRING SECURE VOICE COMMUNICATION. COST COMPONENTS INCLUDE: BACKBONE NETWORK AND COST OF DIGITIZATION DEVICES - PURCHASE PRICE PER DIGITIZATION DEVICE ASSUMED $2,000.

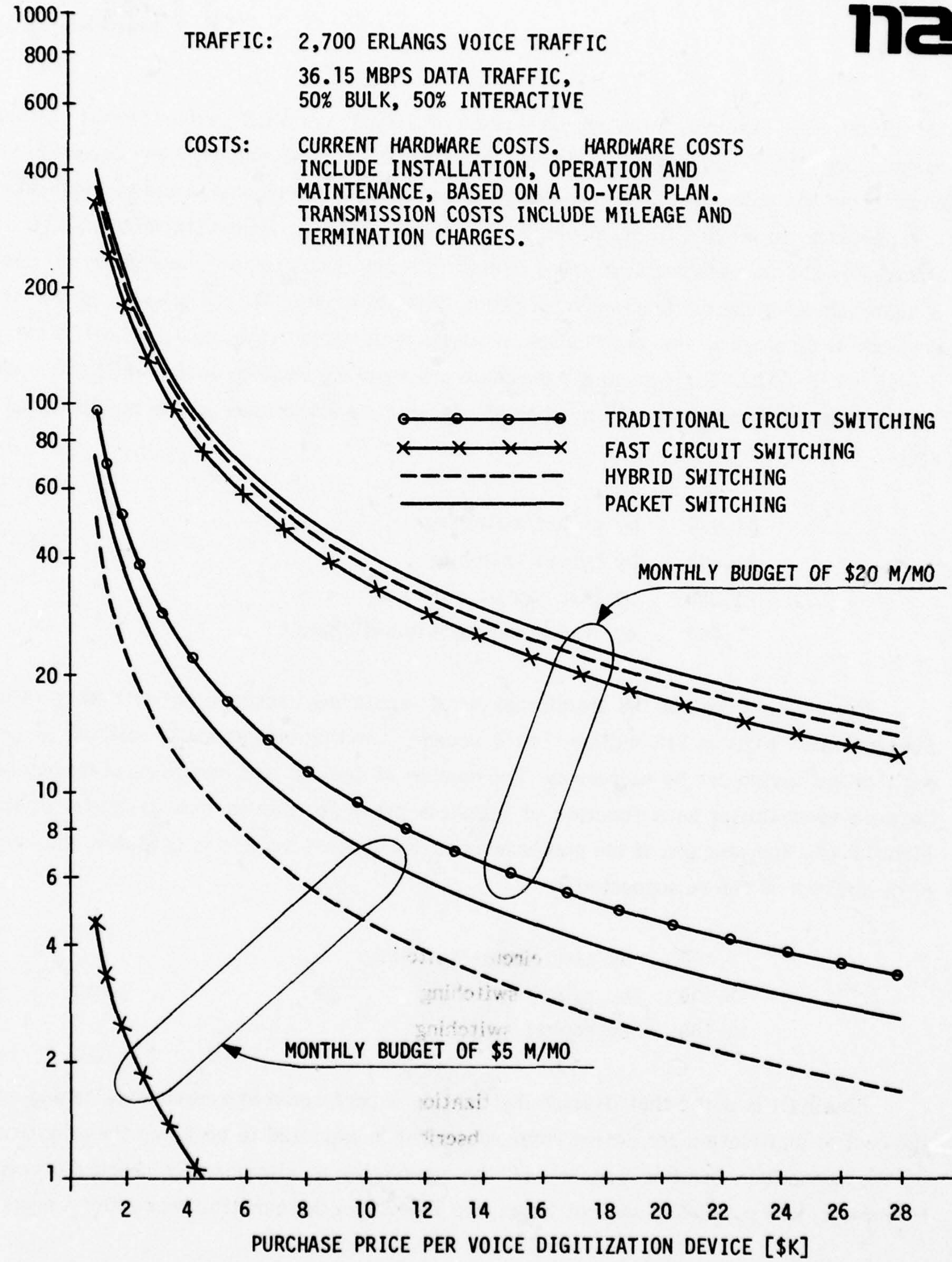

FIGURE 3.13: NUMBER OF VOICE DIGITIZATION DEVICES WHICH CAN BE SUPPORTED BY SWITCHING TECHNOLOGIES - AS A FUNCTION OF PURCHASE PRICE PER DIGITIZATION DEVICE - UNDER FIXED MONTHLY BUDGET FOR THE BACKBONE NETWORK AND DIGITIZATION DEVICES - THE VOICE DIGITIZATION RATE IS 8 KBPS.

$5 million. For example, for a purchase price of $10,000 per VDR device, packet switching can support 41,000 devices and traditional circuit switching can support 9,000 devices. When considering the mixed digitization strategy of digitizing in the backbone and at the handsets, it is necessary to provide 15,912 devices in backbone switches. Hence the mixed digitization strategy is not feasible for traditional circuit switching when the purchase price per device is higher than $6,000, under a budget of $20 million per month. On the other hand, for other network technologies, the digitization strategy is feasible when the purchase price per device is below $22,000. Assuming a purchase price per digitization device of $4,000 and the mixed digitization strategy, the number of secure voice subscribers which can be supported are:

87,000	by packet switching
81,000	by hybrid switching
71,000	by fast circuit switching
7,000	by traditional circuit switching

The monthly cost of the traditional circuit-switching backbone network when voice is digitized at 8 Kbps is $16 million; hence under a monthly budget of $5 million, no voice digitization device can be supported. The number of devices that can be supported by other network technologies as a function of purchase price per digitization device is shown in Figure 3.13. For example, if the purchase price per digitization device is $4,000, the number of devices which can be supported is:

1,100	by fast circuit switching
11,400	by hybrid switching
17,700	by packet switching

Finally it is noted that if voice digitization is performed in backbone switching nodes, the cost of digitization per active voice subscriber is expected to be lower than digitization in the subscriber handset because of the possibility of dynamically sharing processing resources. This possibility was not taken into account in the quantitative results presented.

COST/PERFORMANCE STUDIES IN SWITCHING TECHNOLOGIES

4.1 INTRODUCTION

This chapter presents quantitative results of cost/performance studies for each of the alternative network technologies. The results expose the cost differences for alternative realizations and usage of a given network technology. Section 4.2 reports the backbone network cost for the circuit-switching technology as a function of interactive user duty cycle. A comparison between the alternative network technologies as a function of user think time (gap between messages in interactive data applications) is also provided. Section 4.3 provides a comparison between the fixed and moveable boundary frame management strategies for realizing a hybrid-switched system. This section also reports the sensitivity of hybrid-switched backbone network cost to different mixes of bulk and interactive data applications, the packet size for bulk data applications, and priorities. The circuit subnet cost component in hybrid-switched systems is also shown as a function of voice digitization rate. Cost/performance studies for packet-switched networks are reported in Section 4.4. This includes a comparison of the fixed path protocol and the path independent protocol for speech communication and the impact of the composite packet option. Finally, vocoder bit rate evolution scenarios for DOD are postulated and the backbone costs for these scenarios between 1980 and 1995 are given.

4.2 COST OF CIRCUIT-SWITCHED NETWORKS AS A FUNCTION OF DUTY CYCLE

The inefficiency of traditional circuit switching results from the dedication of transmission facilities to users for the duration of the call. Fast circuit switching is an attempt to reduce the inefficiency by accommodating interactive users by individually switching the distinct message during an interactive session. The cost of circuit-switching technologies for integrated voice and data strongly depends upon the duty cycle of a typical interactive user session. The results of Chapter 3 were derived under the following assumptions: an interactive user sends or receives a total of 200 messages per session on the average; the message size is 1,000 bits; and the gap between successive messages is 10 seconds. As was discussed in Chapter 3, these values closely agree with the results of measurements in [FUCHS, 1970] when encompassing traffic flow in both directions—from user to computer and from computer to user.

In this section the cost of traditional circuit-switching networks is studied as a function of average think time and average message size. This study also facilitates a more detailed comparison between traditional circuit switching and fast circuit switching.

Figure 4.1 shows the backbone network cost of a traditional circuit-switched network as a function of the interactive message size. The networks are designed for 2,700 Erlangs voice traffic and 36.15 Mbps data traffic, 50% of which is interactive. The voice digitization rate is parameterized at four values ranging from 2.4 Kbps to 64 Kbps. The strong dependence of traditional circuit switching on the interactive message size is apparent, since the backbone network cost decreases by 71% to 81% as the interactive message size increases from 1,000 to 10,000 bits. In actual applications, few interactive applications are characterized by messages longer than 5,000 bits with the possible exception of high-speed graphics.

Figure 4.2 shows the cost of traditional circuit switching as a function of think time of interactive users. If the think time (representing gaps between interactive messages) decreases, the inefficiency of dedicating transmission facilities to such users decreases, resulting in a reduction in the cost of the circuit-switched network. An important breakpoint is the think time below which traditional circuit switching is more effective than other switching technologies. The following observations are made from Figure 4.2:

- *When the think time is less than 1.2 seconds, traditional circuit switching is more cost-effective than fast circuit switching.*

TRAFFIC: 2,700 ERLANGS VOICE TRAFFIC DIGITIZED AT THE VDR RATES INDICATED.

36.15 MBPS DATA TRAFFIC, 50% BULK, 50% INTERACTIVE

COSTS: CURRENT HARDWARE COSTS. HARDWARE COSTS INCLUDE INSTALLATION, OPERATION AND MAINTENANCE, BASED ON A 10-YEAR PLAN. TRANSMISSION COSTS INCLUDE MILEAGE AND TERMINATION CHARGES. COST OF DIGITIZATION DEVICES NOT INCLUDED.

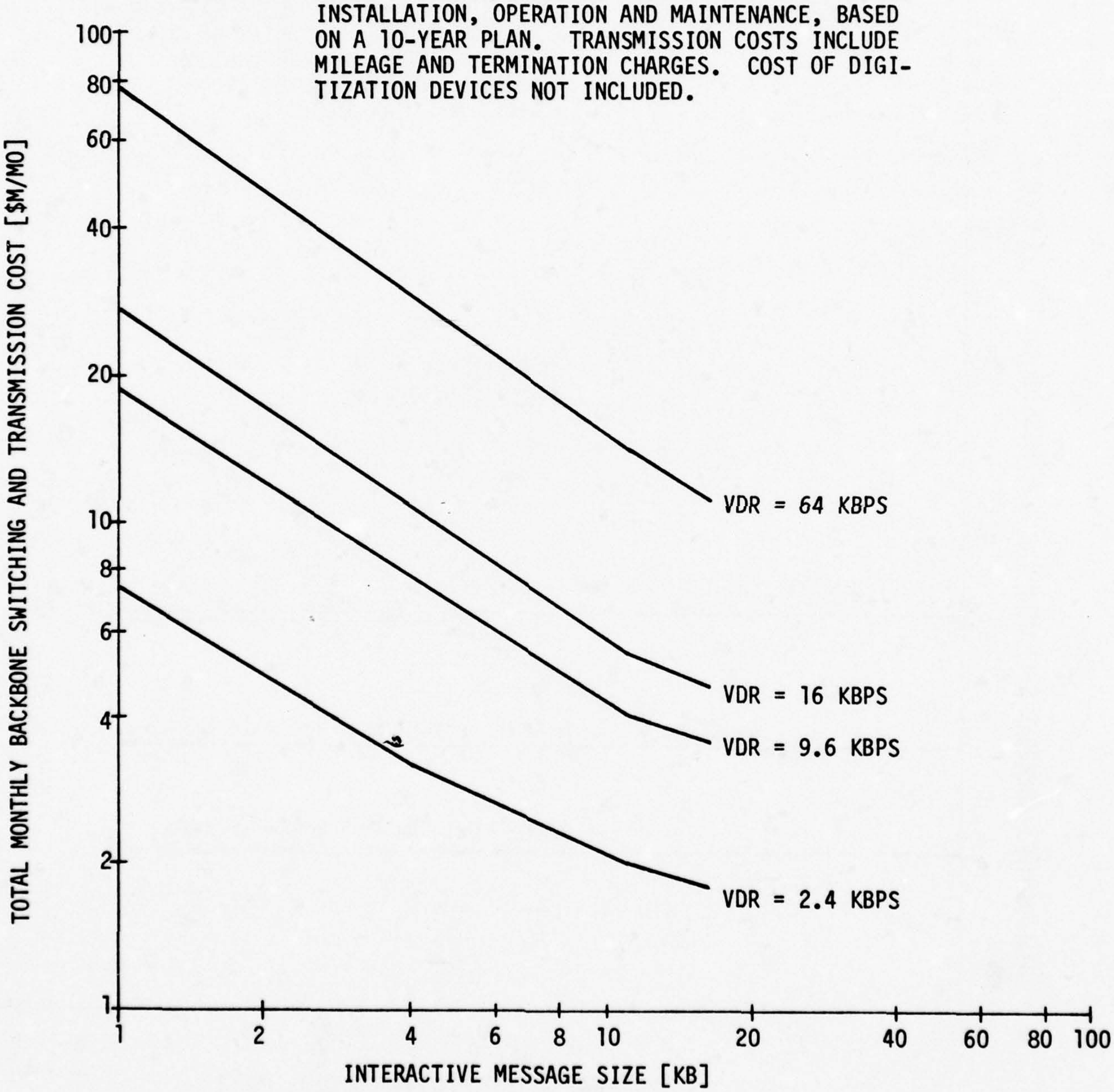

FIGURE 4.1: TRADITIONAL CIRCUIT-SWITCHING: COST AS A FUNCTION OF INTERACTIVE MESSAGE SIZE

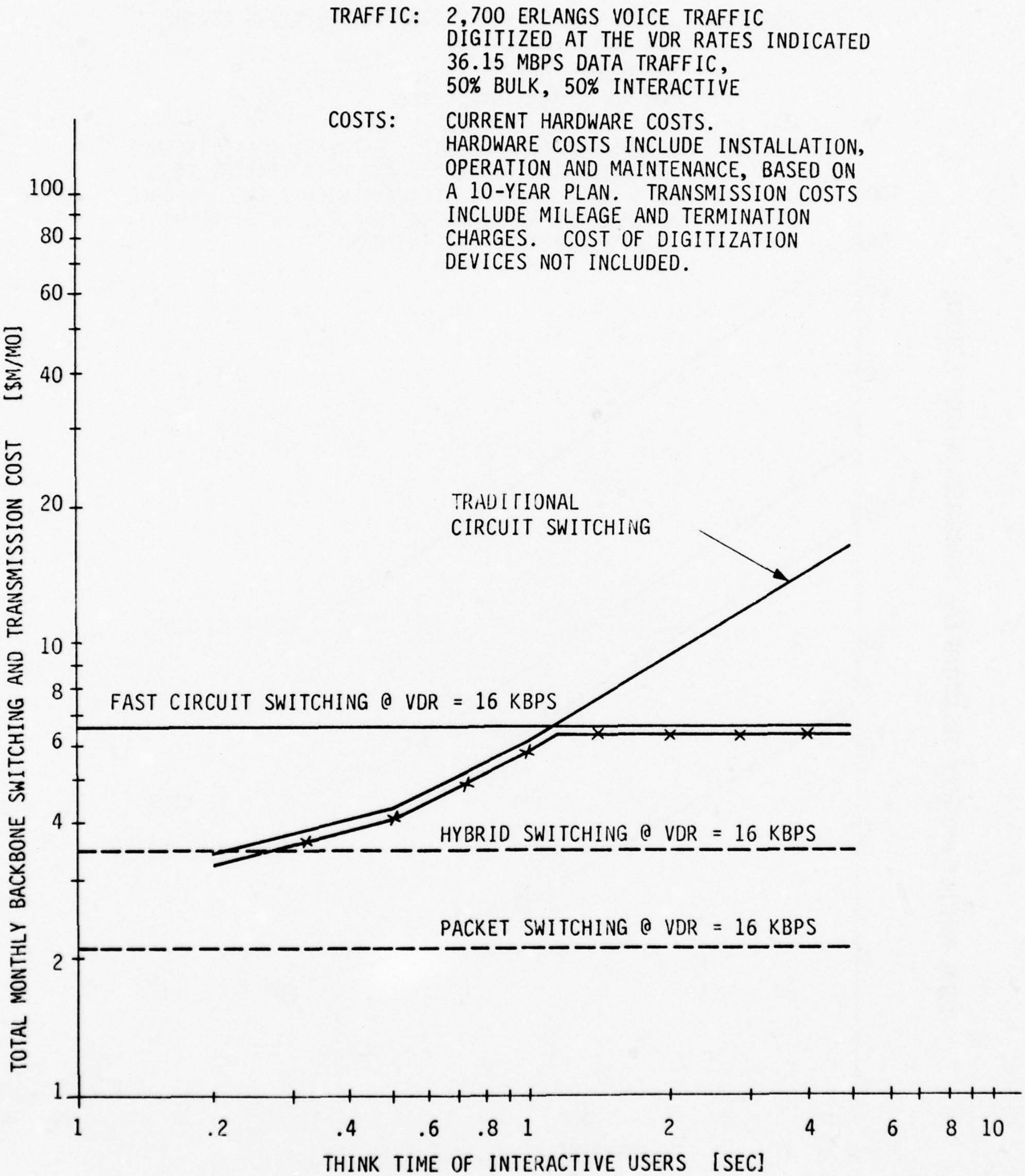

FIGURE 4.2: TRADITIONAL CIRCUIT SWITCHING: COST AS A FUNCTION OF INTERACTIVE USER THINK TIME

- *When the think time is below 220 msec, traditional circuit switching is more cost-effective than hybrid switching.*

- *Packet switching is more cost-effective than traditional circuit switching over the entire range of think time considered.*

It is assumed for fast circuit switching that circuit setup or disconnection required 140 msec. Nevertheless, traditional circuit switching becomes more cost-effective than fast circuit switching for setup times greater than 280 msec, since not only is transmission capacity wasted during circuit setup and disconnection, but switching cost is significantly higher in fast circuit switching than in traditional circuit switching. Hence, reducing this switching cost compensates for some of the cost of idle transmission capacity (between the 1200 and 280 msec).

Traditional circuit switching becomes more cost-effective than hybrid switching at very low values of think time because of the complexity (and hence cost) of the hybrid switch. Both dedicate transmission capacity to voice conversations. Traditional circuit switching does not become more cost-effective than packet switching, even when no capacity serves idle interactive users, because packet switching also prevents dedication of capacity to silence periods in voice conversations. That is, if there are no gaps between interactive data messages, circuit switching would efficiently accommodate data applications. The cost difference between traditional circuit switching and packet switching would then reflect the difference between how well the network technologies accommodate voice traffic.

The results reported in this section suggest a hybrid mode of operating a circuit-switched network—using traditional circuit switching when the gap between interactive messages is small, and using fast circuit switching when the gap between interactive messages is large. This combination would result in a cost function for the backbone network as a function of message gap (think time) as shown in Figure 4.2. The point where the advantage changes depends upon the interactive message size, the voice digitization rate, and the switch cost to implement the hybrid strategy.

4.3 *COST/PERFORMANCE STUDIES IN THE HYBRID-SWITCHING TECHNOLOGY*

4.3.1 Cost Component Composition in Hybrid Switching

In the investigation of hybrid-switching cost/performance tradeoffs, costs are decomposed into the circuit and packet-switching subnet cost components and the switching and transmission cost components. Figure 4.3 shows the major cost components as a function of VDR. The cost breakdowns are based on hybrid-switching network design using the moving boundary frame management strategy. However, similar trends have been observed for the fixed boundary frame management strategy. The costs shown are for backbone networks designed for the nominal traffic scenario including 2,700 Erlangs and 36.15 Mbps data traffic of which 50% is interactive data. Nominal network performance criteria are used: voice loss probability of 0.01; 200 msec average end-to-end delay for interactive packets of 800 bits; and 600 msec end-to-end delay for bulk application packets of 1,200 bits.

The righthand side of Figure 4.3 shows the breakdown of the backbone network cost into switching and transmission cost components. The total monthly cost of switching ranges from $1.3 M/mo at VDR = 2.4 Kbps to $1.55 M/mo at VDR = 64 Kbps. This is equivalent to a purchase price range of $2.7 M to $4.4 M per switch, under the assumption that all eight backbone switches are of equal size. The lefthand side of Figure 4.3 shows the total monthly backbone network cost and the circuit-switched subnet cost component. The circuit-switched subnet cost component reflects the cost of a network accommodating only voice traffic. The additional cost component includes the incremental transmission and switching costs required to carry the data traffic. Two observations can immediately be made:

- *The circuit-switched subnet cost component increases very rapidly with VDR, from 20% at VDR = 2.4 Kbps to 80.4% at VDR = 64 Kbps.*

- *The switching cost component is nearly constant with VDR and the cost increase is mostly in transmission facilities. Hence the percentage of the switching cost decreases rapidly as a function of VDR, from 55% at VDR = 2.4 Kbps to 24.4% at VDR = 64 Kbps.*

TRAFFIC: 2,700 ERLANGS VOICE TRAFFIC DIGITIZED AT THE VDR RATES INDICATED. 36.15 MBPS DATA TRAFFIC. 50% BULK, 50% INTERACTIVE.

COSTS: CURRENT HARDWARE COSTS. HARDWARE COSTS INCLUDE INSTALLATION, OPERATION AND MAINTENANCE, BASED ON A 10-YEAR PLAN. TRANSMISSION COSTS INCLUDE MILEAGE AND TERMINATION CHARGES. COST OF DIGITIZATION DEVICES NOT INCLUDED.

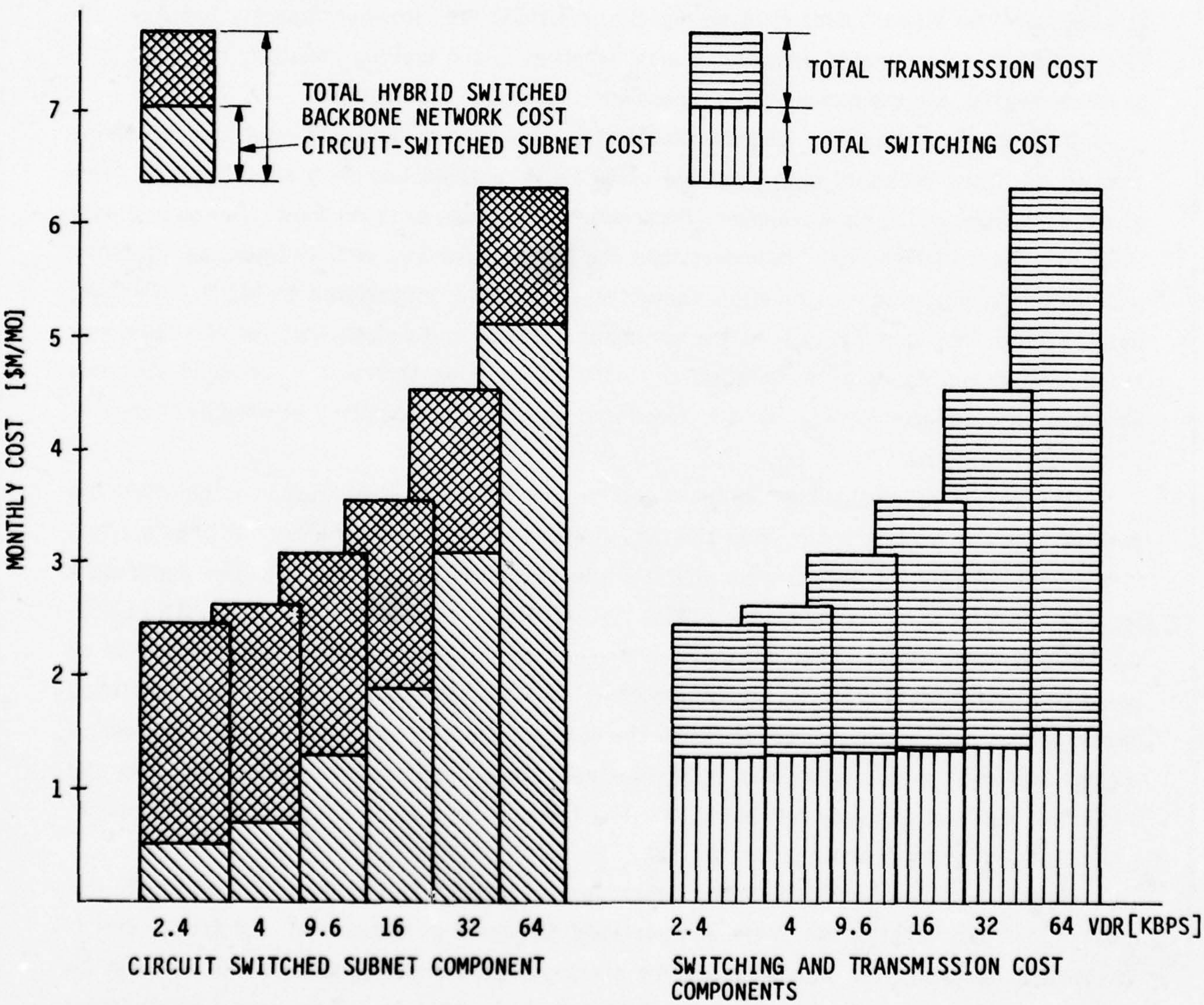

FIGURE 4.3: MAJOR COST COMPONENTS IN HYBRID SWITCHING

Further analysis of the cost components reveals that only a small fraction of the switch cost can be attributed to circuit switching. The bulk of the cost is associated with the inclusion of packet switching and of dynamic management functions.

4.3.2 Fixed Vs. Moving Frame Management Strategy in Hybrid Switching

One of the fundamental decisions regarding operational alternatives of hybrid-switching networks is the choice between fixed and moving boundary frame management strategies. The fixed boundary case rigidly partitions link channel capacity between the circuit-switched and packet-switched traffic whereas in the moving boundary case, packet-switched traffic can use excess capacity assigned to circuit switching.

It is apparent that the transmission cost in the moving boundary case will be lower than in the fixed boundary case. On the other hand, a fixed boundary switch should have lower cost because it is less complex. Surprisingly, however, analysis shows that switch cost is slightly higher for the fixed boundary than the moving boundary case because, as discussed in Chapter 2, a higher transmission capacity requirement contributes to higher switching cost. Figure 4.4 shows the cost of the backbone network and switch cost for the fixed and moving boundary cases as a function of VDR. From this figure, it is evident that the absolute cost difference between the fixed and the moving boundary strategies increases with the voice digitization rate.

The object of comparing the fixed and moving boundary strategies is to quantify the cost savings provided by the moving strategy relative to the fixed strategy. In simple cases it has been possible to demonstrate that the moving boundary strategy provides significant savings (say ~ 20%) [GITMAN, 1977], [FISCHER, 1976], [NETWORK ANALYSIS CORPORATION, 1977]. For example, one can demonstrate that substantial amounts of packet-switched data can be accommodated on the temporarily idle circuit-switched capacity of a single link. However, when the entire system operating under high volumes of circuit-switched traffic examined, only relatively small savings are achieved because the additional channel capacity needed in the fixed boundary case is obtained at a "discount" because of economy of scale in the tariffs.

Apart from cost-effectiveness, other factors affect the comparison of fixed and moving boundary strategies. These are partially discussed in Chapter 2. Additional risk is involved in adopting the moving boundary strategy since more complex switches must be developed. Moreover, the fixed boundary strategy has certain merit in that it is a natural evolutionary step for combining DOD voice and data communications.

TRAFFIC: 2,700 ERLANGS VOICE TRAFFIC DIGITIZED AT THE VDR RATES INDICATED. 36.15 MBPS DATA TRAFFIC, 50% BULK, 50% INTERACTIVE

COSTS: CURRENT HARDWARE COSTS. HARDWARE COSTS INCLUDE INSTALLATION, OPERATION AND MAINTENANCE, BASED ON A 10-YEAR PLAN. TRANSMISSION COSTS INCLUDE MILEAGE AND TERMINATION CHARGES. COST OF DIGITIZATION DEVICES NOT INCLUDED.

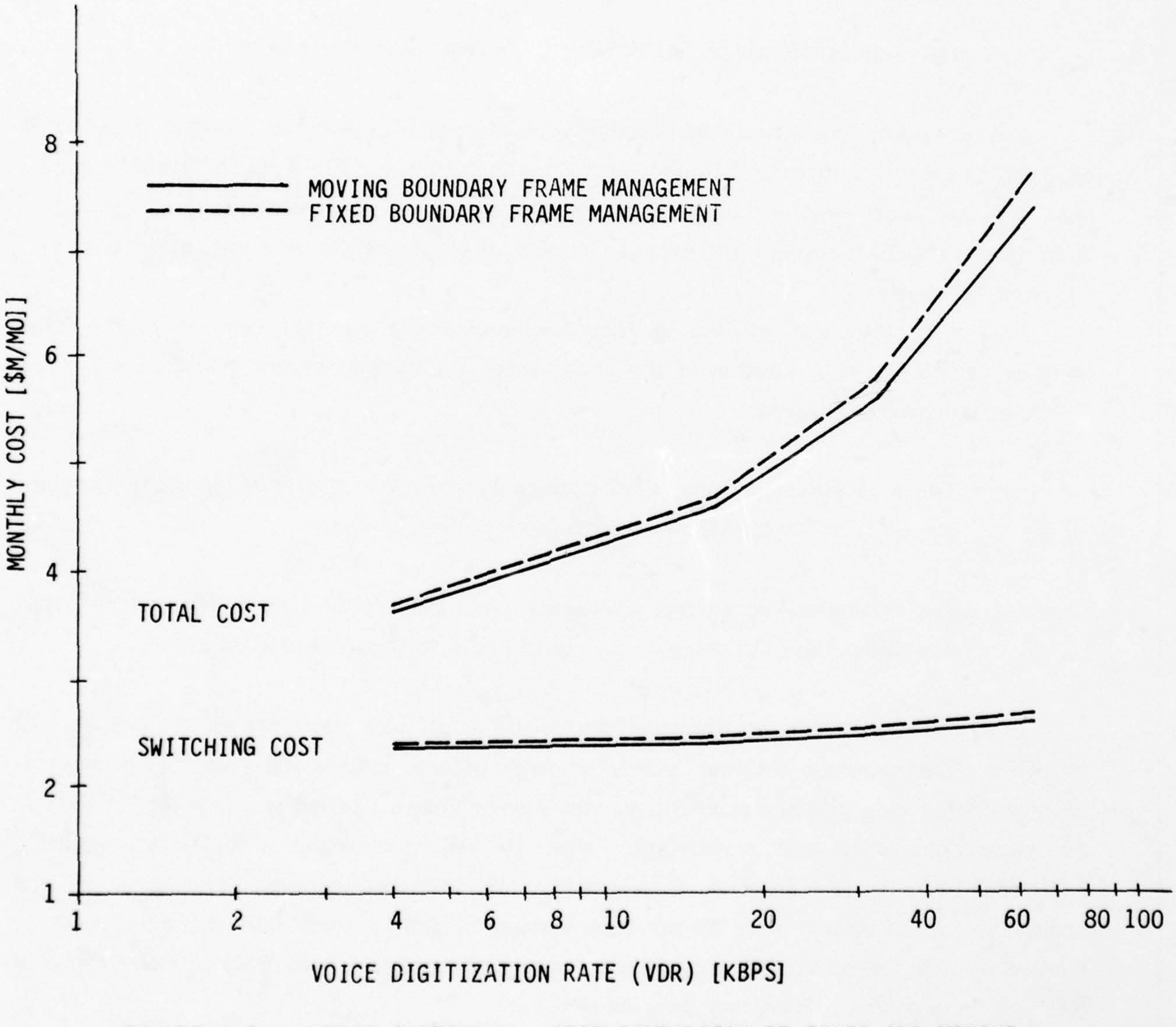

FIGURE 4.4: HYBRID SWITCHING: COST COMPARISON OF FIXED AND MOVING BOUNDARY FRAME MANAGEMENT STRATEGIES

It has been previously demonstrated [NETWORK ANALYSIS CORPORATION, 1977] that the most significant factors affecting the cost difference between fixed and moving boundary strategies are:

- *The circuit and packet-switched traffic mix*
- *The voice digitization rate*
- *The engineered loss probability for the circuit-switched subnet.*

For example, when the loss probability is decreased, a higher channel capacity is required to carry the circuit-switched load. This in turn results in a higher average excess capacity for packet-switched traffic under the moving boundary strategy. The latter deduction is apparent because the average number of busy circuits remains constant under a constant Erlang load.

The percentage cost savings of the moving boundary strategy relative to the fixed boundary strategy, as a function of the above three variables is shown in Figure 4.5. The following conclusions emerge:

- *The total savings of the moving boundary strategy relative to the fixed boundary strategy, in the backbone network cost, is less than 5%.*
- *The percentage of savings decreases when the packet-switched data throughput increases while the voice circuit-switched throughput is held constant.*

The last conclusion is somewhat surprising and may even appear to be counter intuitive. The rationale follows: when the voice offered load is fixed and the network is designed for a constant loss probability, the average excess capacity available for data in the moving boundary case is constant. When the data throughput is increased, requiring additional capacity, the fraction of excess capacity becomes smaller. This factor and the economies of obtaining incremental transmission capacity, results in the extra cost of transmission for fixed boundary operation increasingly offset by the greater switching cost of the more complex moving boundary switch.

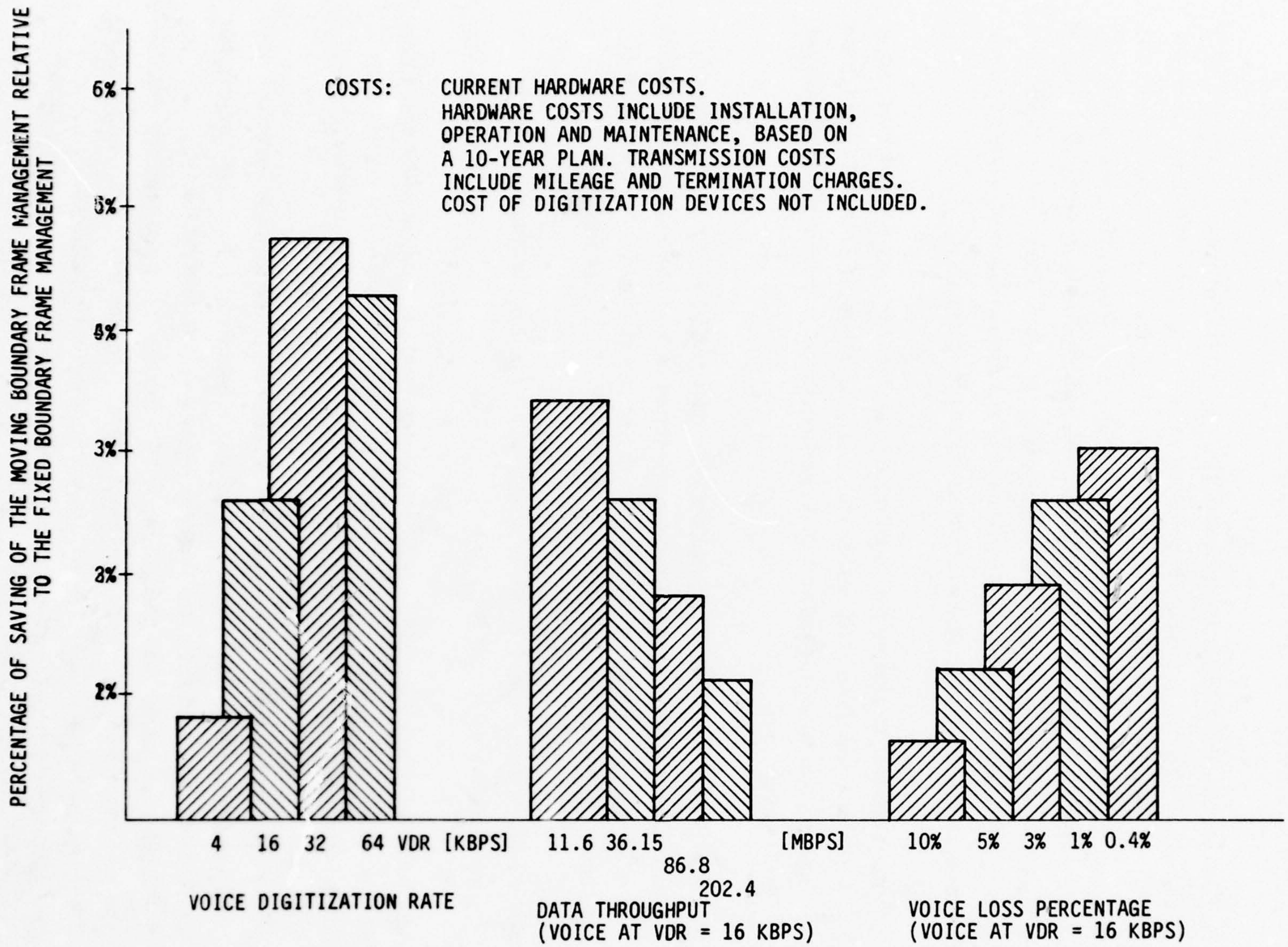

FIGURE 4.5: HYBRID SWITCHING: PERCENTAGE OF SAVINGS OF THE MOVING BOUNDARY FRAME MANAGEMENT STRATEGY RELATIVE TO THE FIXED BOUNDARY FRAME MANAGEMENT STRATEGY, AS A FUNCTION OF VDR, DATA THROUGHPUT, AND VOICE BLOCKING PROBABILITY

4.3.3 Cost Sensitivity of Hybrid-Switching Options

The first issue investigated is the cost sensitivity of hybrid switching to different data traffic compositions and design options, under fixed voice throughput. Figure 4.6 shows the total cost of a hybrid-switched network as a function of the composition of bulk and interactive data applications with the packet size of the bulk data traffic as a parameter. The cost differences under the priority or non-priority case for the interactive data traffic are also shown. The total data traffic is held constant at 36.15 Mbps. The networks are designed for a 200 msec average end-to-end delay for the interactive traffic and 400 msec delay for a bulk data packet. The following observations are made:

- *The data traffic composition significantly impacts the total network cost. Cost variations are from 11% to 37.8% over the range of 10%-90% bulk data applications, when the network is properly designed with a large packet size for bulk applications.*

- *The packet size design variable for bulk data traffic is significant, especially when the bulk data constitutes a large fraction of the total data traffic. A cost difference of 25.8% is observed when the packet size varies between 1,000 bits and 10,000 bits, when bulk data constitutes 90% of the data traffic.*

- *Giving higher priority to the interactive traffic does not significantly impact total backbone network cost.*

Another issue investigated is the sensitivity of the total backbone network cost to the engineered probability of loss for circuit-switched traffic. Analysis of the results leads to the following conclusion:

- *Total hybrid network cost is nearly constant over a wide range of loss probability. When the end-to-end voice loss is increased from 0.4% to 10%, the total cost reduction for the fixed boundary policy is less than 4.5% and for the moving boundary less than 2.1%. Network cost is insensitive to the loss parameter because of the high traffic level. Higher loss causes only a slight decrease in the number of circuits which is in turn offset by some increase in switching cost resulting from a higher degree of alternate routing.*

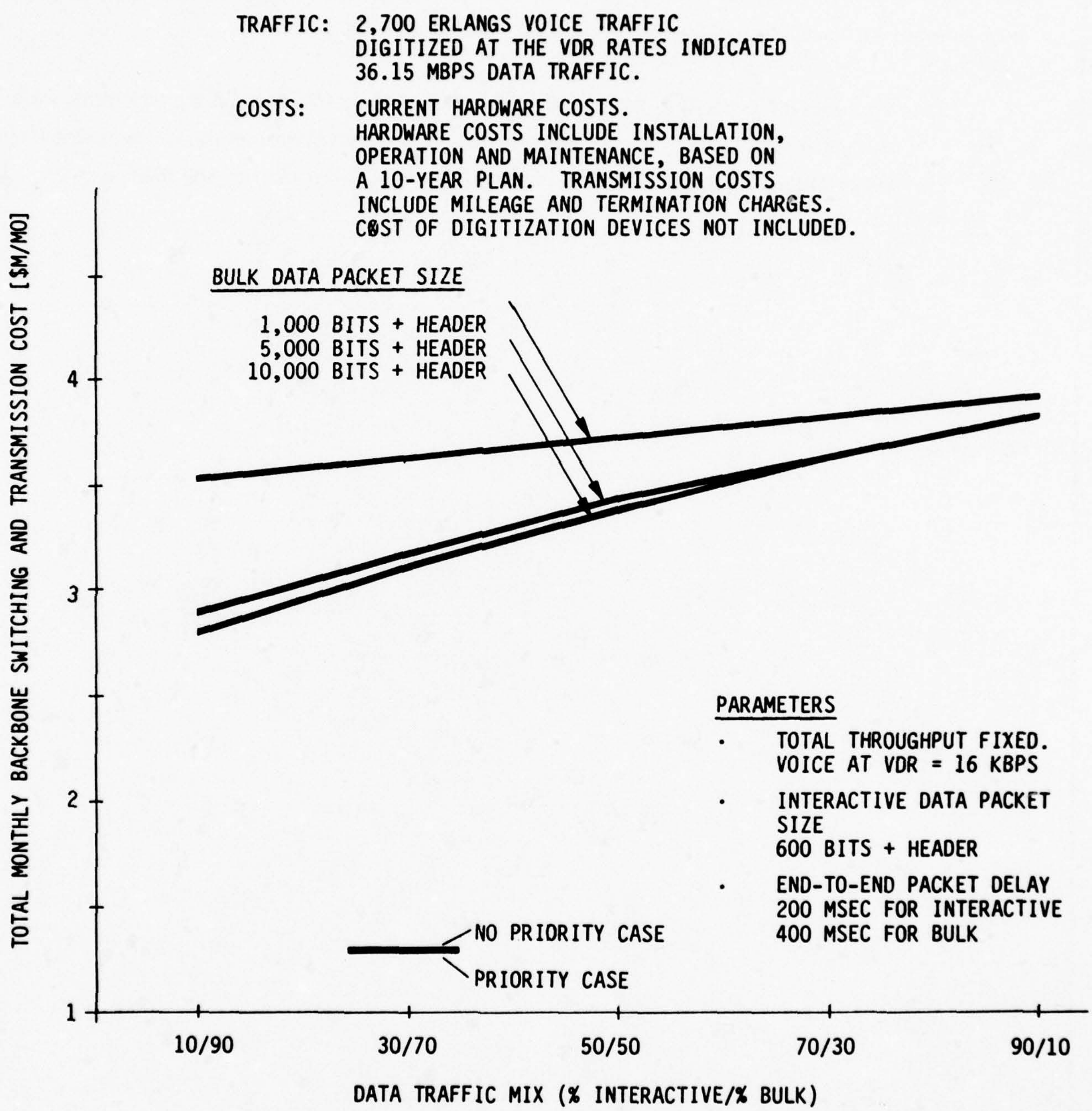

FIGURE 4.6: COST SENSITIVITY IN HYBRID SWITCHING TO: TRAFFIC MIX, PACKET SIZE, AND PRIORITY

The sensitivity to data throughput variations with a fixed voice throughput is investigated next. The results for the fixed and moving boundary strategy, including the cost components are shown in Figure 4.7. One can observe that:

- *The cost of switching increases much faster than the cost of transmission when the data throughput is increased. When the data throughput is increased to 202.4 Mbps, the switching cost component constitutes 49% of the total cost.*

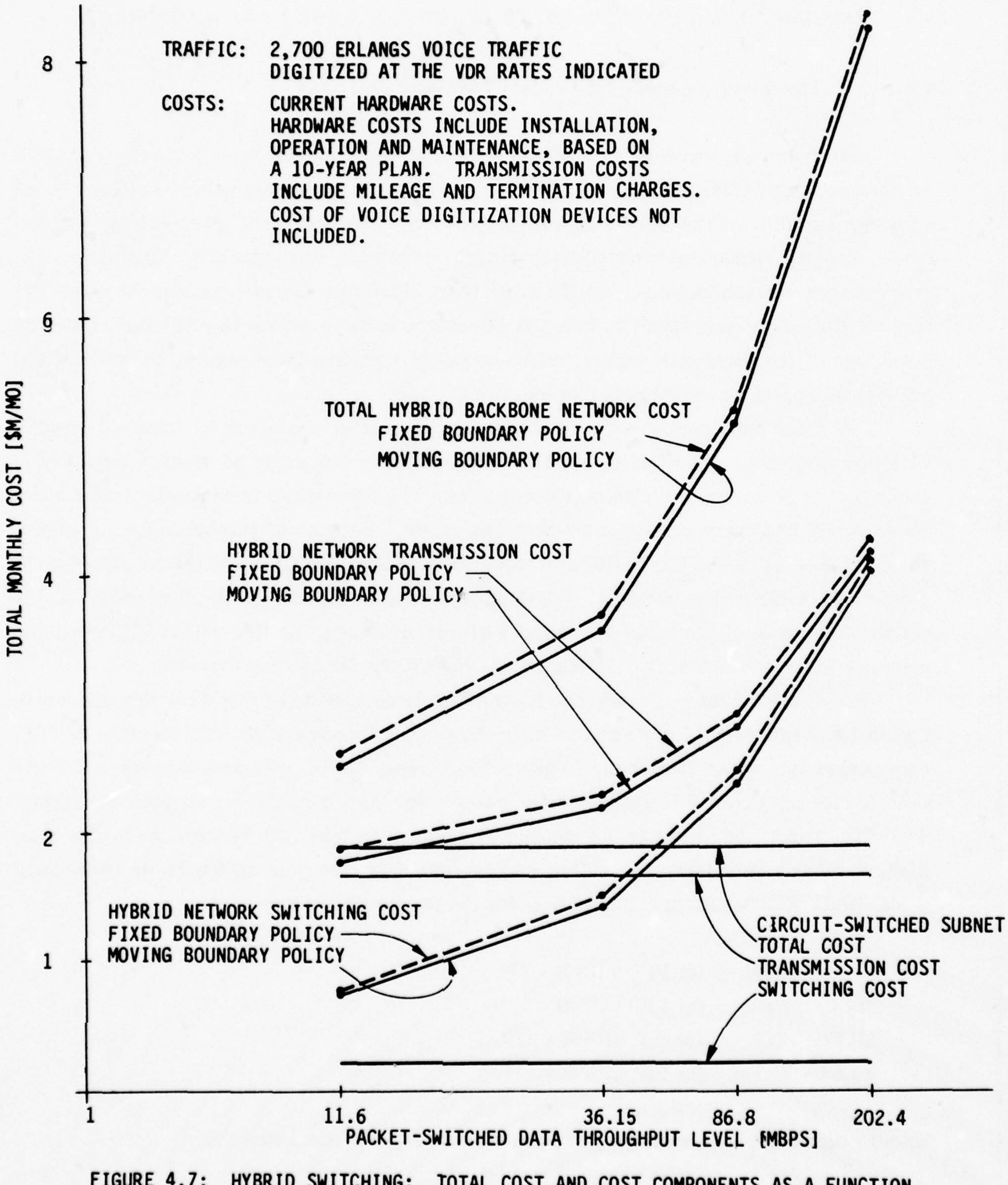

FIGURE 4.7: HYBRID SWITCHING: TOTAL COST AND COST COMPONENTS AS A FUNCTION OF DATA THROUGHPUT

4.4 COST/PERFORMANCE STUDIES IN PACKET VOICE AND DATA NETWORKS

4.4.1 Fixed Path Vs. Path Independent Transport Protocols

The choice of Fixed Path Protocol (FPP) vs. Path Independent Protocol (PIP) is a fundamental high-level protocol issue in the operation of integrated packet switched voice and data networks. The path independent protocol is more robust, more readily adapted from existing packet-switching technology, and has compatability advantages in internetwork communications. On the other hand, the larger header requirement under PIP may require longer packetization delay at the source node to reduce header overhead. The advantage of the fixed path protocol is in the use of an abbreviated header, once the "fixed path" is set up, hence reducing header overhead.

The fixed path packet voice protocol has properties analogous to those of circuit-switched networks. Specifically, a path must be set up (although no channel capacity is dedicated) prior to transmission of voice packets, and voice packets belonging to the same conversation must traverse the same path thereafter. Because of this procedure, a packet voice network using the fixed path protocol is more vulnerable to direct enemy attack or to component failure. For example, if a link in the network fails or is temporarily out of operation because of jamming, the voice conversations using the link will be disrupted and will have to be reinitialized by setting up new fixed paths for these conversations.

Quantitative results of backbone network costs comparing FPP and PIP are developed. Figure 4.8 shows the cost of packet voice networks as a function of VDR. Two cases of FPP, with packet headers of 48 bits and 96 bits and two cases of PIP, with packet headers 152 bits and 256 bits are shown. The results presented are for the composite packet protocol option.

The packet size used in the designs are not optimized with respect to header size, VDR, or other parameters. The end-to-end average delay for which the network is designed is 200 msec. The header overhead ranges for the four protocols are:

3.6% - 16.7%	for FPP with H = 48
7% - 21%	for FPP with H = 96
10.6%- 30%	for PIP with H = 152
16.6%- 34.7%	for PIP with H = 256

Despite the appreciable variations in packet overhead, it is concluded that:

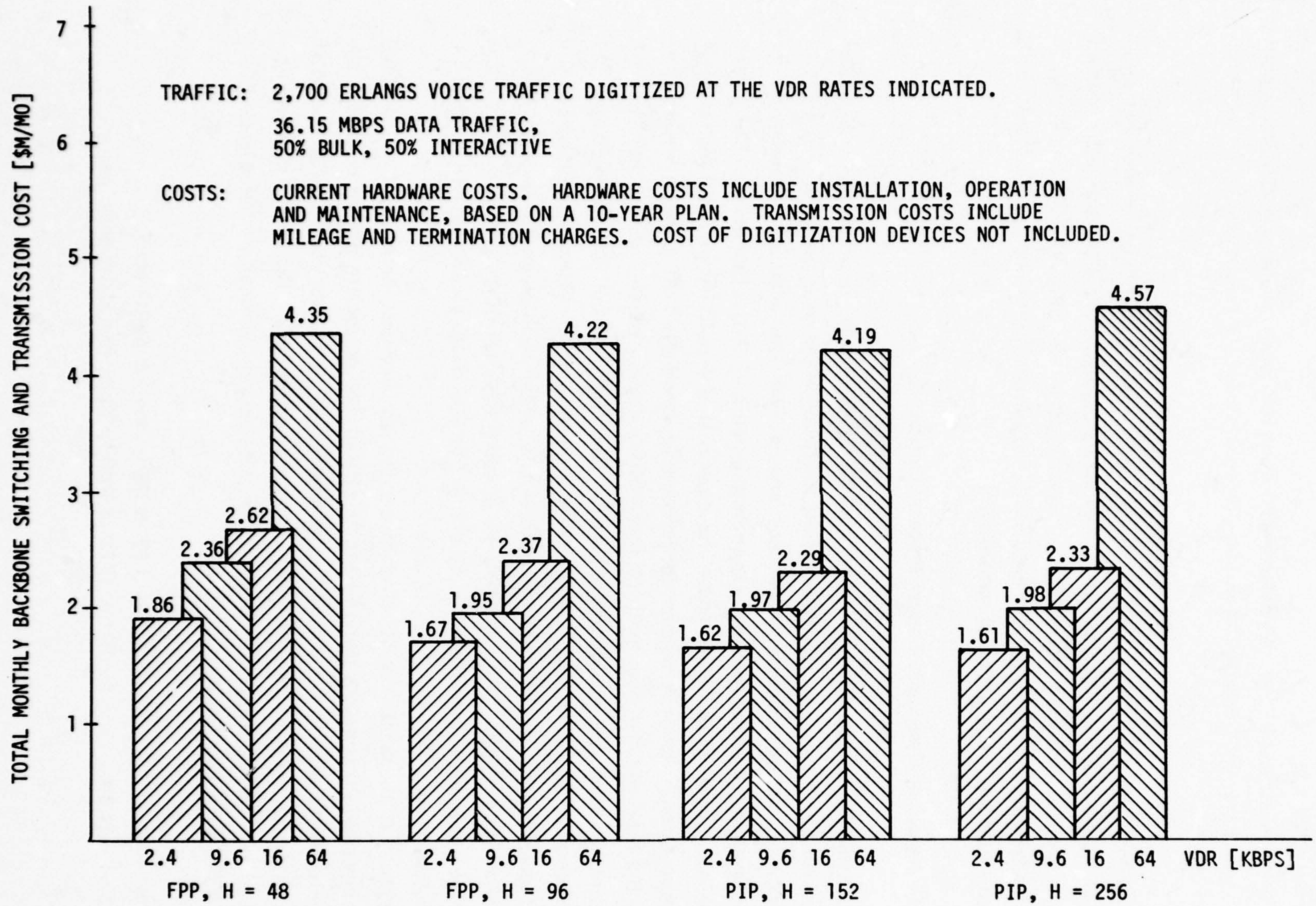

FIGURE 4.8: PACKET SWITCHING: COMPARISON OF FIXED PATH PROTOCOL (FPP) AND PATH INDEPENDENT PROTOCOL (PIP), WITH THE COMPOUND PACKET CASE

- *No significant cost differences are observed when comparing the fixed path protocol and the path independent protocol under the composite packet protocol option.*

It would be premature to state that indeed no cost differences exist between networks utilizing the alternative protocols. It is recommended that these alternatives be studied with more detailed modeling and optimized packet sizes. In comparing FPP and PIP, it would be important to quantify the significant differences between the protocols with respect to robustness, reliability and survivability.

4.4.2 *Impact of Composite Packet Protocol Option*

The issue of composite packets, as treated in the study, impacts only the packet header overhead. Although all speech packets are transported with an end-to-end delay of 200 msec, the switch processing does not account for the additional complexity for multiplexing-demultiplexing speakers at the origination and destination nodes. The impact of composite packets is examined under the fixed path and path independent packet voice transport protocols. The path independent protocol is investigated with packet headers of 96 bits and 152 bits, and the fixed path protocol with a packet header of 96 bits. The path independent protocol was not investigated (for low VDR) without the composite packet option because an excessive packetization delay is incurred at low voice digitization rates in order to guarantee a header overhead below 50% while simultaneously keeping packet construction time small. For example, at a voice digitization rate of 2.4 Kbps, it is necessary to wait more than 100 msec to obtain 256 bits of speech without the composite packet option.

Figure 4.9 shows the costs of packet-switched backbone networks for the three protocol options investigated, each with and without the composite packet options. The networks were designed to accommodate the nominal 2,700 Erlangs voice traffic and 36.15 Mbps data traffic, of which 50% is interactive data applications. The costs are shown as a function of the voice digitization rate. The range of packet overhead for voice packets for the three designs shown are:

7% - 21%	for H = 96 (FPP or PIP), with composite packets
13% - 44.4%	for H = 96 (FPP or PIP), without composite packets

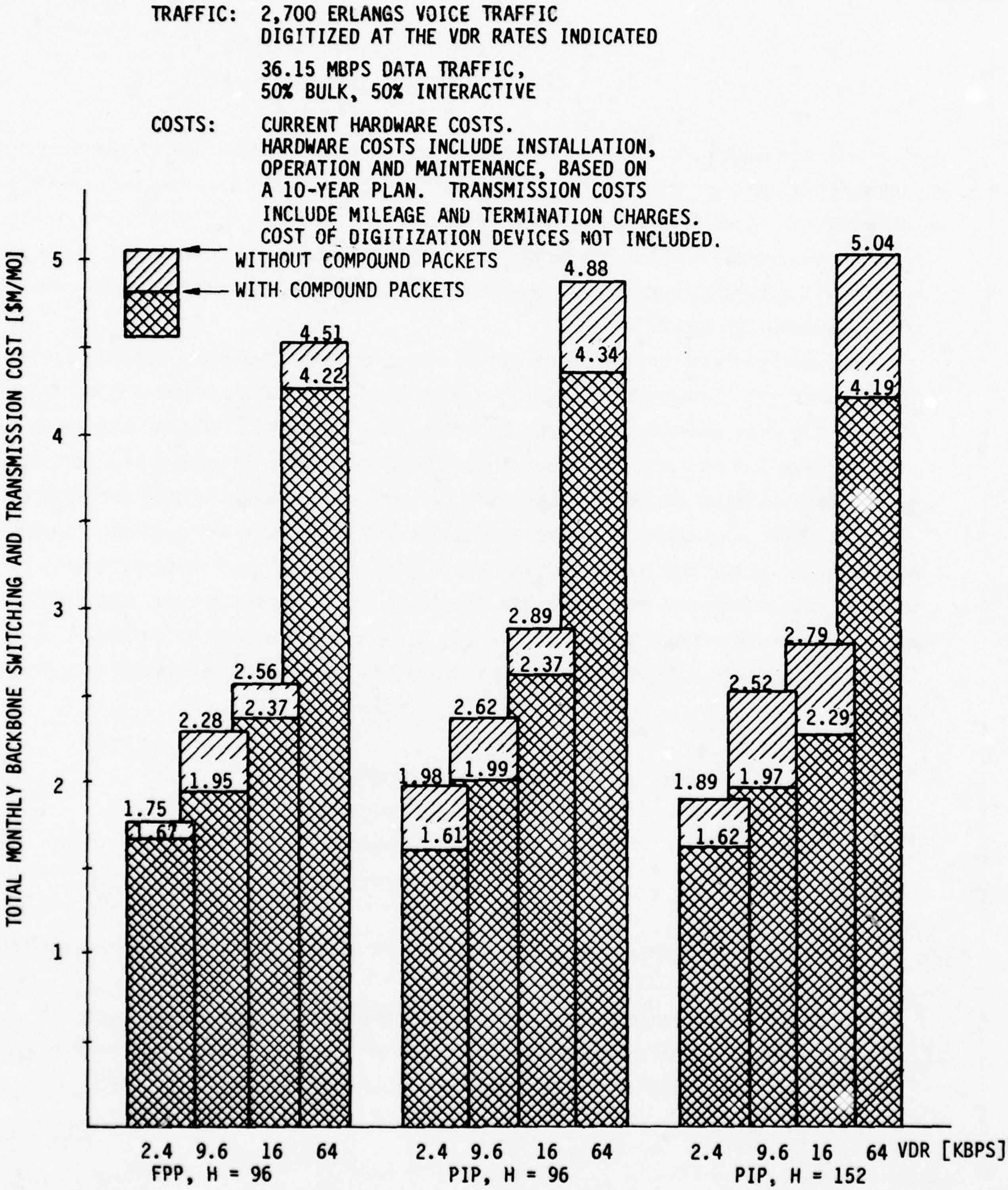

FIGURE 4.9: PACKET SWITCHING: COMPARISON OF COSTS WITH AND WITHOUT COMPOUND PACKETS (FPP-FIXED PATH PROTOCOL, PIP-PATH INDEPENDENT PROTOCOL)

10.6% - 30%	for H = 152, PIP, with composite packets
19.2% - 44.2%	for H = 152, PIP, without composite packets

One can observe in Figure 4.9 that the savings resulting from use of the composite packet option are more significant under the path independent protocol than under the fixed path protocol. Specifically, in the FPP case, the cost reduction in the backbone network from the incorporation of the composite packet option ranges between 4.6% and 14.5% over the range in voice digitization rate considered. The corresponding cost reduction under PIP ranges between 11% and 24%.

The sensitivity of the composite packet option to the mix of voice and data traffic is investigated next. Designs are obtained for a constant voice offered load of 2,700 Erlangs with varying data throughput between 11.6 Mbps and 202.4 Mbps. Figure 4.10 shows the total backbone network cost as a function of VDR with the data throughput as a parameter. All the designs shown are for the fixed path protocol with a packet header size of 96 bits. The cost differences shown for each throughput level are those between the composite packet option case (lower bound) and the case without composite packets (upper bound). The absolute cost differences relative to the composite packet option are not significant and moreover, the percentage savings obtained by using composite packets decreases as data throughput increases. Specifically, for the entire VDR range, the percentage cost savings observed are:

7.7% - 22.9%	for 11.6 Mbps data throughput
6.3% - 14.5%	for 36.15 Mbps data throughput
4.8% - 8.6%	for 86.8 Mbps data throughput
2.8% - 4.4%	for 202.4 Mbps data throughput

The above results are not surprising and indeed substantiate the following conclusion:

- *The cost savings resulting from implementing the composite packet protocol depend on the composition of voice and data traffic. The savings are significant when the fraction of voice traffic in the network is high.*

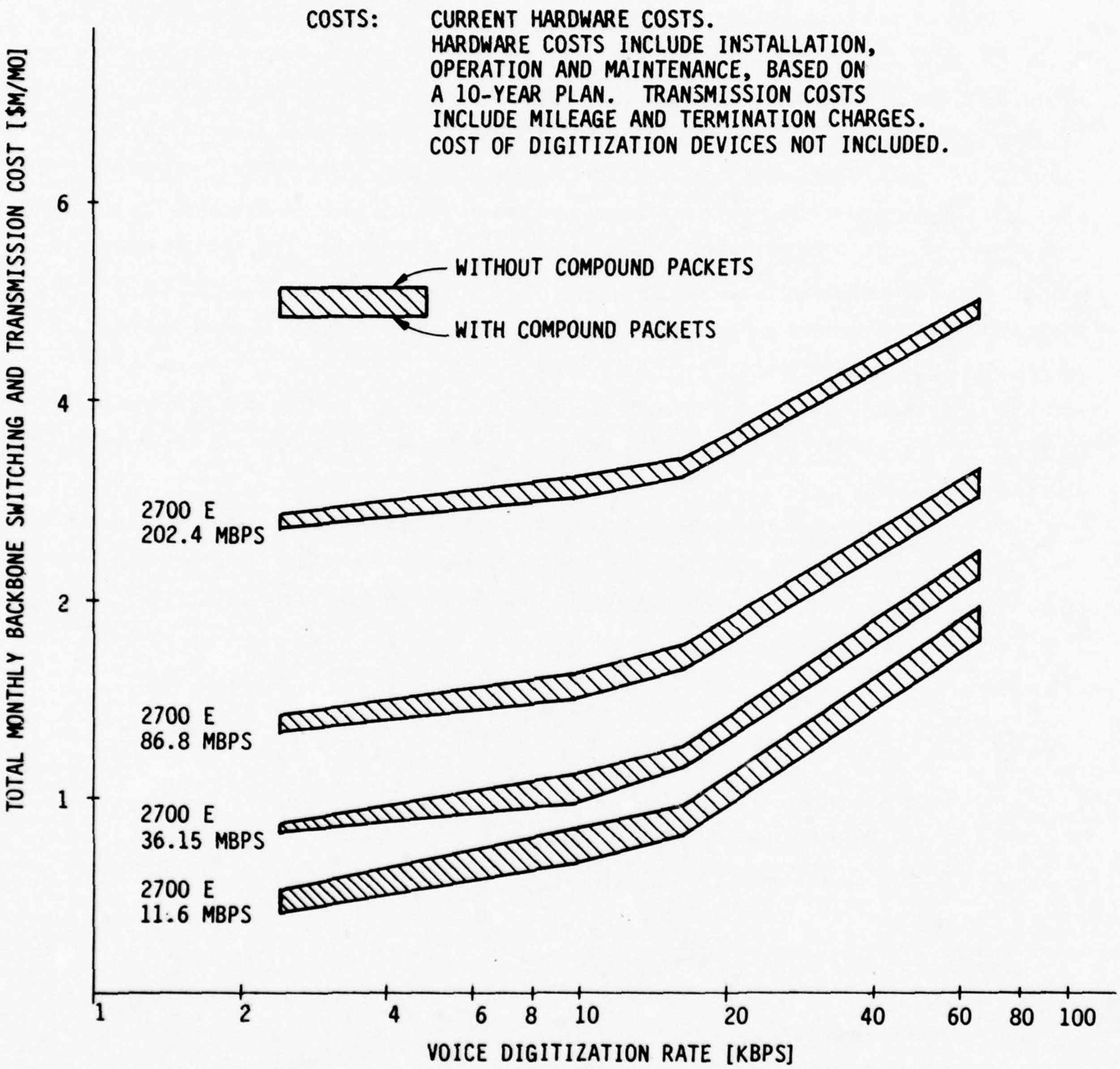

FIGURE 4.10: PACKET SWITCHING: COST AS A FUNCTION OF VOICE DIGITIZATION RATE FOR DIFFERENT DATA THROUGHPUT LEVELS (FIXED PATH PROTOCOL, H=96)

4.4.3 Possible Evolution of an Integrated DOD Voice and Data Network

It is expected that any future integrated DOD voice and data network will include a variety of voice digitization devices. However, in general, it is expected that the fraction of low VDR devices will increase. To investigate the cost trend of the backbone network resulting from potential VDR evolutionary trends, the two VDR evolution scenarios shown in Table 4.1 are used. Scenario 1 is based on the assumption that DOD will promote the use of a 2.4 Kbps digitization rate; hence, the percent usage of this VDR is increased from 5% in 1980 to 60% in 1995. Other VDR's in this scenario are 9.6 Kbps, 16 Kbps, and 32 Kbps. The general trend is increasing availability of low VDR devices resulting in a reduction of the average VDR. Scenario 2 assumes that DOD will promote a vocoder at 8 Kbps; hence, its percentage is increased from 15% in 1980 to 70% in 1995.

The AUTODIN II data traffic and the AUTOVON voice traffic are assumed as the initial traffic requirements in 1977 with a scenario of 2% annual growth for voice and 10% annual growth for data.

The packet-switched backbone network costs are obtained under two different packet voice transport protocols and packet voice header sizes. The data traffic is switched in the same manner under all alternatives examined. The following design options are used for the evolution between 1980 and 1995:

<u>Option 1</u>

VDR Scenario 1
Fixed Path Protocol for Packet Voice
Packet Voice Header is 96 bits.

<u>Option 2</u>

VDR Scenario 2
Fixed Path Protocol for Packet Voice
Packet Voice Header is 96 bits.

nac

TABLE 4.1: VOCODER VDR EVOLUTION SCENARIO: PERCENTAGE OF VOCODER VDR COMPOSITION

VDR VALUE	YEAR 1980	1985	1990	1995
Scenario 1				
2.4 Kbps	5%	25%	35%	60%
9.6 Kbps	15%	25%	35%	30%
16 Kbps	40%	30%	20%	10%
32 Kbps	40%	20%	10%	-
Scenario 2				
2.4 Kbps	5%	15%	20%	20%
8 Kbps	15%	35%	55%	70%
16 Kbps	40%	30%	20%	10%
32 Kbps	40%	20%	5%	-

Option 3

VDR Scenario 2
Path Independent Protocol for Packet Voice
Packet Voice Header is 256 bits.

The evolution of the total backbone network cost and the cost components are shown from 1980 to 1995 in Figure 4.11. No general cost trend can be observed. In most cases, the total backbone network cost decreases with time; however, one can observe a cost increase in 1995 as compared to 1990 for vocoding Scenario 2. There are three major factors which impact the total cost: the average VDR, the traffic requirements, and the packet header overhead. When the average VDR is decreased, the packet header overhead increases because of the necessity to maintain low packetization delay. The increase in traffic requirements and in the packet overhead tend to increase total cost, while the reduction in the average VDR tends to decrease the network cost. For example, the backbone network cost increases between 1990 and 1995, under Scenario 2, because the reduction in the VDR is much smaller than the increase in the traffic requirements. The average vocoder VDR decreases by 20% while the data traffic increases by 60% and the voice traffic by 10% in the same period.

During the period from 1980 to 1995, the average VDR decreases from 20.76 Kbps to 5.92 Kbps for Scenario 1 and from 20.52 Kbps to 7.68 Kbps for Scenario 2, while the traffic requirements increase by 35% for voice and by 417% for data.

This study demonstrates that cost of the backbone communications network remains nearly constant over a period of 15 years, while the traffic requirements increase substantially over the same period. This has implications on system engineering in that it enables the design of a cost-effective network for a relatively long time span, providing the algorithms for dynamic sharing of resources are implemented.

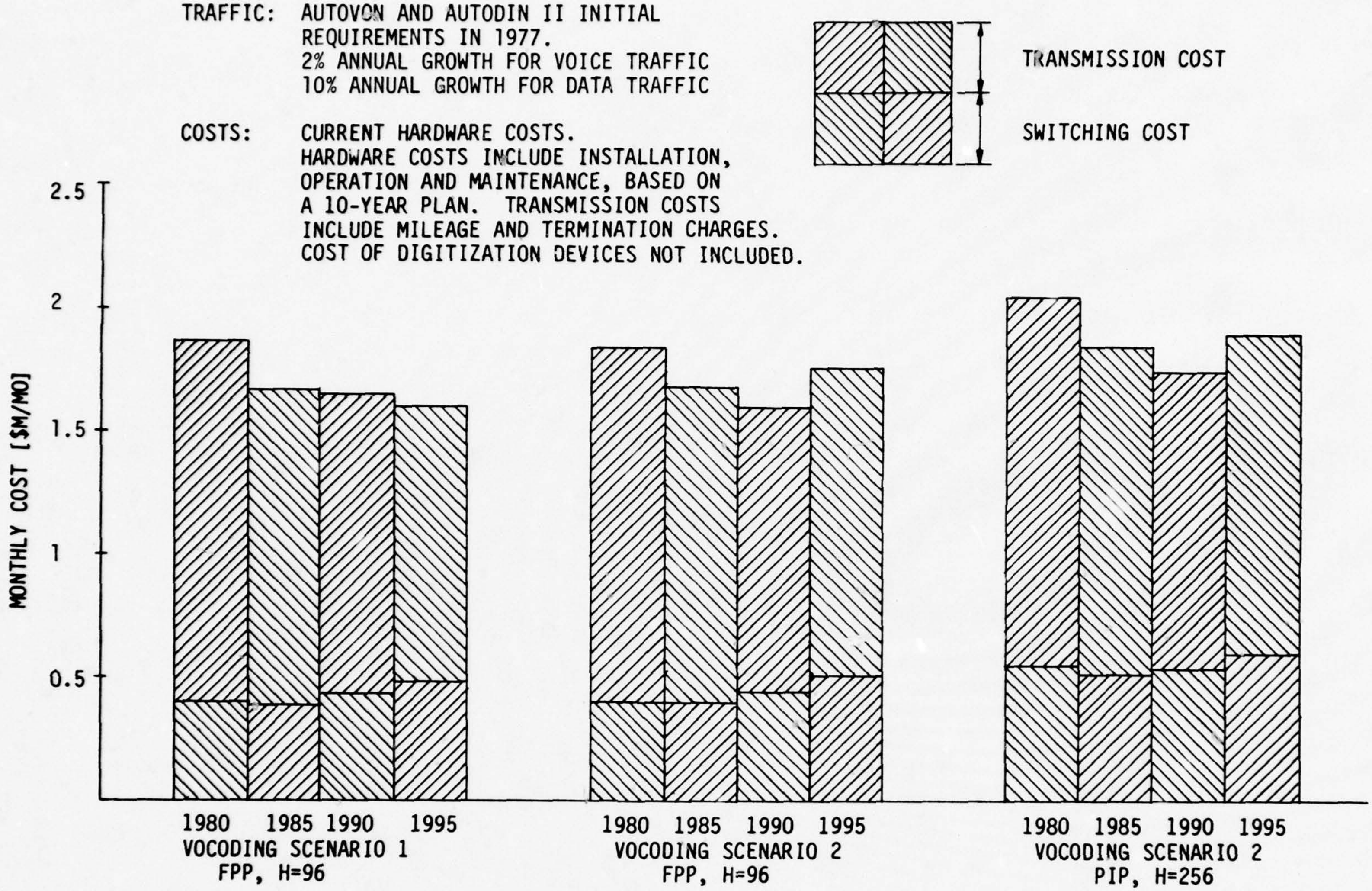

FIGURE 4.11: EVOLUTION OF THE COST OF A DOD PACKET-SWITCHED BACKBONE NETWORK FOR INTEGRATED VOICE AND DATA FOR VOCODING SCENARIOS IN TABLE 4.1 (FPP-FIXED PATH PROTOCOL, PIP-PATH INDEPENDENT PROTOCOL)

CONCLUSIONS AND FURTHER RESEARCH

5.1 CONCLUSIONS

This report presents a comprehensive study of fundamental DOD voice and data communications issues. The focus is on concerns for DOD communications systems for the mid-1980's and beyond. These are assumed to utilize digital switching and transmission facilities. The major issues investigated are:

- The economics of integrating voice and data applications in a common communications system.
- The comparison of alternative switching technologies for integrated voice and data networks.
- The cost-effectiveness of alternative voice digitization rates and strategies.

The above issues were investigated using relatively detailed protocol scenarios. The impact on transmission and switching costs of the communications protocols characterizing the alternative switching technologies were evaluated, and the sensitivity of the conclusions were tested in detail with respect to operational alternatives, traffic composition variations, network design and performance parameters, and large variations in the price of switching and transmission.

Alternative strategies for voice digitization were investigated. Among these are: digitization at the backbone network, digitization at the subscriber handset, and a combination of the two strategies, whereby users requiring end-to-end secure voice communications have digitizers at the handset and all other conversations are digitized at the backbone network. The costs of the network technologies were investigated under alternative voice digitization strategies as a function of the price of voice digitizers.

Most comparisons were based on the backbone network switching and transmission cost and the cost of voice digitization devices when applicable. In some cases, such as for voice digitization at the subscriber handsets, the cost of local access was included for the comparisons. In these cases, the cost of the local distribution systems were assumed equal

to the cost of the backbone network, on the basis of previous results [NETWORK ANALYSIS CORPORATION, 1975], [NETWORK ANALYSIS CORPORATION, 1976] .

Numerous qualitative and quantitative results are reported. Some of these results are summarized below:

- *On the basis of total backbone network cost (transmission and switching), the ranking of switching technologies in increasing cost for integrated voice and data is: packet switching, hybrid (circuit-packet) switching, fast circuit switching, traditional circuit switching.*

- *The ranking of switching technologies remains virtually unchanged under a variety of traffic, cost, and parameter assumptions, with packet switching providing the lowest cost networks for all cases studied. This conclusion is independent of whether voice and data are carried on separate networks or on a single integrated network.*

- *The backbone network costs of alternatives to the packet-switching technology range from 30% to over 1,700% higher than packet switching. Packet switching remains superior to the other technologies even if switching or transmission costs decrease by a factor of ten.*

- *For any network technology, the voice digitization rate adopted by DOD is a significant factor affecting the cost of future DOD integrated voice and data networks. Traditional circuit switching can achieve the greatest savings by using low bit rate voice digitizers. However, even with 2.4 Kbps voice digitizers, traditional circuit-switching network costs are higher than costs of packet-switching networks utilizing 64 Kbps digitizers. It is recognized that low bit rate voice systems may encounter speech quality degradation under noisy environments, and the lowest rate devices may not be acceptable throughout the DOD. However, the superiority of the packet-switching technology was demonstrated over the entire (2.4 Kbps - 64 Kbps) VDR range. Furthermore, both the relative and absolute cost savings achieved by packet switching increase as the voice digitization rate increases.*

* *Backbone network cost was found to be insensitive to parameter and performance variations such as: engineered blocking probability (.04 to .1) for circuit-switched applications, end-to-end average packet delay (200 msec to 600 msec), and priority alternatives. This conclusion holds for each of the alternative network technologies, where applicable. Additionally, several cases were examined where voice packet delays were constrained to be 50 msec (rather than 200 msec). These lead to packet network cost increases of 1% - 3% and showed that the packet network cost is insensitive to the average delay over a wide delay range.*

* *The moving boundary frame management strategy in hybrid switching was demonstrated to be slightly more cost-effective than the fixed boundary frame management strategy. However, the cost difference appeared to be insignificant with an upper bound of 5% within the range of parameters investigated.*

* *An important factor in hybrid switching is the partition of the traffic between circuit-switched and packet-switched services. With hybrid switching, bulk data applications should either use a longer packet size or be served by the circuit-switched subnet. Design options which use a mix of long and short packets are viable when high bit rate communication channels are used. Such channels are required for high traffic volumes, and thus, do not impose additional cost for systems studied.*

* *Security considerations may dictate that voice digitizers are placed at the subscriber handsets rather than at the backbone nodes. This implies that the total cost of the voice digitizers may become an appreciable component of the total system cost. Under this option, the absolute cost savings of the packet-switching technology with respect to any of the alternatives is expected to be larger than the values obtained because of substantial savings achievable in the local and regional distribution networks under the packet-switching technology.*

* *While detailed security issues were not investigated, if link encryption is used to protect the backbone communication channels, packet switching requires fewer encryptors (and hence lower cost) because fewer links are needed to meet traffic requirements.*

- *Segregated voice and data networks result in only slight cost increases over an integrated voice and data network for all the network technologies considered.*

- *Segrated packet systems for voice and data cost less than integrated systems using either the hybrid or circuit-switching technologies.*

The above conclusions are based on economic analysis of network technologies. Other factors, not reflected in the cost comparison, which impact the choice of the network technology are briefly discussed.

Applications:

The packet-switching technology is more suitable for applications involving message dispatching to multidestinations and conferencing. The advantages would be reflected in the cost had such applications been included in the study. A further advantage of using packet switching for conferencing is the ability to sustain conference connectivity in the presence of link outages.

Priority and Precedence Levels:

Provision of priorities in a circuit-switched network environment requires dedication of facilities to high priority customers (overdesign) or the need to preempt low priority calls in progress under high load conditions. In the latter case, preempted subscribers may place additional burden on the system by redialing. Packet switching has no inherent need for preemption. The impact of high load, high priority traffic on low priority subscribers is longer packet delays rather than lack of connectivity.

The packet-switching technology can accommodate different access and transport priorities. For example, subscriber A may have higher access priority (ability to establish and sustain communications) than B, yet lower transport priority (no criticality in delivery delay).

Interoperability:

Packet switching is inherently a more suitable vehicle for communications using various media, technologies, and systems (interoperability). With this technology, interoperability is accomplished via "gateways" which interface different networks. Interoperability is expected to be a significant problem during the evolution of DOD communications to an integrated system, in particular, if reliance on existing facilities is to be maximized. Furthermore, interoperability is expected to be a continuous requirement for communications between subscribers in strategic and tactical systems.

Security:

An integrated DOD communications system is expected to provide message security by end-to-end and/or link encryption. One of the design objectives in providing security is the protection of system performance (availability and responsiveness). It is noted that switching technologies which establish and dedicate end-to-end resources are more vulnerable with link encryption techniques using link synchronization where the receiving crypto derives key synchronization by counting characters in the received data stream. Once the encryption devices lose synchronization (e.g., by short duration jamming) reestablishment may require a relatively long period of time. Naturally, messages using a dedicated circuit will be lost, but more significantly, the end-to-end dedicated circuits which utilize the desynchronized link may have to be reestablished.

Risk:

The circuit-switching technology is relatively simple and well established, and thus, the use of circuit switching minimizes the risk of development and implementation. Although the long-term lowest cost network technology alternative is packet switching, analog and digital circuit-switched networks for voice are expected to be used during the transition period.

5.2 DISCUSSION AND FURTHER RESEARCH

During the preparation of this report, extensive reviews and critiques of the results have been conducted by ARPA, DCA and members of the technical community. Although none of the results were challenged, the reviews raised important questions relative to the validity of the results under different data bases, model assumptions and design criteria, and in particular, the validity of the results and conclusions when considering extended systems which include local access and satellite channels. For the benefit of the reader, we briefly discuss the major questions that have been raised.

The results of this study initially appear quite surprising and perhaps nonintuitive. Indeed, the results were at first surprising to the authors as well, and an extensive effort of experimentation and sensitivity analyses was necessary to understand and rationalize each result and conclusion. To the authors' knowledge, no study of the magnitude reported has been previously done for a detailed comparison of switching technologies over such a broad range of data bases, cost variations, and network design criteria. Hence, the scope of the study does not enable an outside reviewer to easily verify the results without extensive efforts of modeling, algorithm and program development. The main questions raised during the review process are: the impact on the results and conclusions of variations in switch models and parameters; the impact on the total cost comparison of the switching technologies when the local access cost constitutes a high fraction of the total cost; voice intelligibility when packet switching is extended to local access; the appropriateness of the average delay as a criterion for the design of packet voice networks; and the impact on conclusions when silence detection is incorporated into the hybrid-switching strategy. A brief discussion of these issues is provided below:

1. The switch models used in the study are sufficiently detailed to reflect the operation of the switching strategies compared with precision. However, while the cost of switching nodes, as a function of processing, storage, and channel interfaces reflect current costs of computer systems, there are no existing switches which realize all the switching strategies compared. Consequently, it was necessary to make assumptions regarding the number of instructions for processing various functions. These assumptions were based on NAC's knowledge of existing switching nodes and on estimation of the complexity of the particular functions. Nevertheless, one can expect variations in the processing values

assumed depending on computer technology, switch architecture, and the specific implementation of various functions. To test the impact of the assumptions, sensitivity studies were performed as a function of several parameters (e.g., assuming 200 instructions per node for processing a speech packet using the fixed path protocol, instead of 100 instructions) with virtually no changes in the results. Changes in these parameters may slightly impact the quantitative comparison of the switching strategies, but it is NAC's belief that they will not change the relative rankings of these technologies or any of the major conclusions. This belief is supported by the fact that the major results and conclusions remained unchanged over two orders of magnitude of variations of the ratio of switching to transmission cost. Indeed, one may observe that in many cases, if the cost of switching of the more costly alternatives is ignored, the ranking of technologies remains unchanged.

2. Local access cost could be much higher than that of the backbone network cost in some situations (e.g., small number of backbone nodes). In fact, if the number of backbone nodes is small, the system may be hierarchical where lower level switching nodes may exist. However, the cost differences observed for the backbone network are valid, independent of the cost of the local access systems. Obviously, full life cycle costs including development should be eventually considered. The ranking of switching technologies in the local access system is expected to be the same as in the backbone system, as previously discussed. If the ranking remains the same and the cost of the local access is higher than the cost of the backbone system, the absolute cost differences between the alternative switching technologies in the local access system could be higher than in the backbone system.

3. The problem of end-to-end delay for packetized voice, including the local distribution system requires further investigation. There are several ways to insure intelligible packet voice communication including:

   a. Smoothing at the destination for inter-packet arrival variances.

   b. Reducing the end-to-end delay constraint in the backbone network to allow for delay in the local distribution system.

An appreciable part of the delay is packetization delay, and this will occur only once, either at the source terminal or nearest concentrator or switch. Of course, it is not mandatory to packetize in the local distribution system. In this case, packetization and possibly digitization starts in the backbone network, and the results derived here would be directly applicable. Furthermore, a preliminary design with a significantly lower average delay (50 ms) was investigated. This led to an increase in cost for the packet-switching case examined of between 1% and 3.2% over a range of VDR's, protocols, header sizes, etc. Thus, even with a significantly lower delay constraint, the conclusions (for the cases tested) are still valid.

4. The question relative to the appropriate design criterion for packet speech communication was previously discussed in the report. In general, a 95^{th} or 99^{th} percentile of delay could be a more appropriate criterion than the average delay. However, directly using such a criterion is an intractable network design problem, in particular, in the presence of mulitple traffic categories. Hence, the design could be made to satisfy an average delay constraint and the results must be verified via simulation and analytical techniques relating the average delay and the delay distribution. Investigations of packet voice delay distributions at destination nodes and processing requirements for smoothing the packet speech stream to the listener were conducted during this study and are reported in [NETWORK ANALYSIS CORPORATION, 1977] .

5. The costs of hybrid switching, while greater than packet switching by 30% - 64%, could be reduced by incorporating speech silence detection methods. Hybrid-switch costs, which, under our model, are greater than packet-switch costs, would then further increase, but line costs should decrease resulting in reduced total hybrid-switched network costs. However, if appropriate silence detection methods were used, the difference between hybrid and packet switching would probably become a matter of <u>semantics</u> rather than technology. That is, the operation of hybrid switching will be quite similar to that of packet switching, and the cost differences would depend upon the specific implementations of the two schemes.

The objective of this study was to identify and quantify network technologies demonstrating long-term (1980 and beyond) low operating costs. Since line costs were examined on the basis of tariffs and not costs to a common carrier, it should not be assumed that the conclusions automatically translate to the common carrier environment. Our conclusions relate to the large user who leases tariffed lines and leases or purchases hardware. Furthermore, if the potential cost savings of the packet or hybrid-switching technologies are to be realized, a detailed examination of the transition issues to be encountered in evolving from current circuit-switched voice networks must be performed. The examination of this issue is of importance because the compatibility of existing communications technologies is not a solved problem. To the extent that low rate voice digitization networks are required to interface with higher rate systems (either domestically or abroad) higher near-term costs than the costs projected in the report may be encountered.

While conducting this study, new problem areas were identified. These problems are recommended for further study with the objectives of uncovering the risks in the conclusions and quantitative results, as well as broadening the study into local and regional distribution and more detailed protocol formulations. Furthermore, other factors impact the cost and performance measures which were not reflected in the comparisons reported. Some of these factors were previously discussed, and others are discussed in Appendix A. Future research will enable one to take into account these factors in a more direct, quantitative manner. Among the major problem areas recommended for further investigation are:

1. Further study and comparison of hybrid-switching and packet-switching technologies under more detailed protocol scenarios. Although the ranking of these two strategies was consistent throughout the study, the quantitative differences were not extremely large. Furthermore, the hybrid-switching technology may provide a natural evolutionary path for DOD communications towards a total packet-switching technology.

2. Investigation and comparison of local distribution strategies for hybrid and packet-switching networks.

3. Investigation of the most appropriate partition between local distribution and backbone networks for hybrid and packet switching.

4. Investigation of postulated evolution strategies for DOD communications from existing systems to an integrated voice and data communication system.

5. Study alternative concepts for network and message security in an integrated voice and data network.

6. Study the survivability and reliability of integrated voice and data systems under the packet and hybrid-switching strategies.

It is apparent that the above problem areas are natural and necessary for further investigations if additional quantitative information is sought in support of the conclusions of this report. It is equally apparent that the above problems are extremely difficult and that such investigations have not been conducted before. However, the algorithms and computational tools developed for this study, coupled with recent experimental results of the packet radio system [KAHN, 1975] (which is one potential for local distribution) creates an excellent starting condition for such extensions of these results.

TECHNICAL CONSIDERATIONS IN THE ANALYSIS, DESIGN, AND OPERATION OF VOICE AND DATA NETWORKS

A.1 INTRODUCTION

Detailed technical considerations related to network operation which impact the performance and/or the analysis and design of integrated traffic communications are discussed in this appendix. Emphasis is placed on alternative protocols and algorithms which can have a significant impact on network performance and on the efficiency of utilizing network resources. The objective is to describe problem areas which arise from the integration of voice and data into a common network or which result from the newly investigated switching strategies. Areas suggested for further investigation are identified and discussed.

A.2 ROUTING CONSIDERATIONS

A.2.1 Routing Considerations in Hybrid-Switching Networks

The integration of voice and data applications and the availability of the circuit-switching and packet-switching modes of operation necessitates the investigation of "appropriate" operational routing algorithms in hybrid-switched networks. One question that arises is whether the same routing algorithm should be used for the circuit-switched and packet-switched subnets or, alternatively, whether two different algorithms should be provided. Furthermore, if two algorithms are provided, the interaction between the algorithms must be understood.

This section demonstrates that the objectives of routing algorithms for packet switching and circuit switching are different. Desirable properties of routing algorithms for hybrid-switched networks are presented and questions which require further investigation are raised.

Recall that a path used by a sequence of packets (in a packet-switched network without fixed path restrictions) between the same source-destination node pair is dynamically changing, adapting to the best instantaneous route. On the other hand, a path established for a circuit-switched connection is assumed to remain fixed for the duration of the call. It is further assumed that the circuit-switching mode will be used for traffic characterized by long average message length. The efficiency of circuit switching for applications characterized by long message size was previously demonstrated [MIYAHARA, 1975].

Based on the above observations and efficiency considerations, it is noted that the objectives, and hence properties, of a circuit-switched path differ from those of a packet-switched path [GITMAN, 1977] :

- The objective of a "packet path" is to minimize the average delay (or the incremental delay) to the destination. Ordinarily there is no special concern for path length.

- The objective of a "circuit path" is to maximize the probability that a path will be found for the next call arrival by minimizing committed network resources. This has a direct implication on path length, and hence, often necessitates a hierarchical strategy to achieve these objectives.

The fact that a circuit path is maintained for the duration of a call and the assumption that the circuit-switched mode will be used for traffic characterized by long average message size, suggests that the length of a circuit-switched path must be bounded. This does not necessarily result in an increase in the average loss probability since one option to reduce path length is to provide "camp-on" capabilities until a shorter path can be established. For example, for a particular call, consider a case where the shortest path in the network includes two links and three nodes (including source and destination nodes), and an alternate path is provided which includes four links and five nodes. In this case, the network resources consumed via the alternate path is approximately twice the amount of resources via the shortest path. Since the circuit path is held for the duration of the transmission, an approach which permits the establishment of long paths may significantly reduce the "maximum throughput" or the "maximum number of simultaneous connections" in the circuit-switched network, in particular, when average holding times are relatively long. This suggests two desirable properties for a "circuit path" with natural implications for appropriate routing algorithms. These properties are:

1. The length of an alternate path should be bounded as a function of the shortest path length and the call holding time.

2. For a specific length of the shortest path and a set of possible alternate paths, if call holding time increases, the bound on the alternate paths should decrease.

In practice it may be impossible to let a call "camp-on" until an appropriately short path can be established because of the constraints imposed by message delivery delay and circuit setup delay. A sophisticated approach to path establishment may take into account the waiting time on the camp-on facility and the message priority.

Routing algorithms commonly used for end-to-end circuit establishment are characterized by a set of fixed alternatives, which results in a fixed ordered set of possible paths for an origin-destination pair. Circuit establishment is carried out by attempts to complete the path in a predetermined order.

In a hybrid-switched network, it is possible to devise a dynamic routing algorithm for end-to-end circuit establishment similar to adaptive packet routing as used in the ARPANET. The set of outgoing links for a given destination can adapt to changes in network topology resulting from link or node failures (failure adaptation) as well as to variations in the traffic pattern (congestion adaptation). One possible way to realize an

adaptive algorithm is to maintain tables at each node which record the expected incremental blocking probability and the expected incremental delay for a given destination as a function of the outgoing link. These tables can be updated by control messages to neighboring nodes either on a periodic basis or when changes exceed a threshold.

If a moving boundary frame management strategy is implemented, then the issue of the interaction between the packet and circuit routing algorithms must be addressed. Some questions of concern are:

- Should the tables estimating the end-to-end packet delay be updated after reservation of capacity for circuit switching? (Note that the network capacity available for packet switching has changed as a result of the reservation.)

- Should the outgoing link of stored packets be re-examined after circuit reservations? If yes, should it be done periodically?, after every new circuit reservation?, as a function of packet priority?, etc.

A.2.2 Routing Considerations in Circuit-Switching Networks

Routing considerations in circuit-switching network technologies are similar to those discussed for hybrid switching. In the fast circuit-switching technology, a circuit is dedicated for the duration of the call for voice and bulk data applications. For interactive data applications, a circuit is set up when a message is ready to be sent and disconnected at the end of the message transmission. Circuit path length considerations for voice and bulk data applications are the same as discussed for hybrid switching. On the other hand, fast circuit switching of interactive applications is somewhat analogous to packet switching since the path is potentially "rearrangeable" and adaptable to the state of network load for each new message generated during user-computer interaction. Furthermore, the message size (or holding time) is on the order of magnitude used in packet switching. Hence, the establishment of a long alternative path (in the absense of short paths) would not degrade network performance. In traditional circuit switching, a path is dedicated to users for the duration of use for all applications. Hence, the properties proposed for path length in the context of hybrid switching apply equally for this network technology.

The tradeoffs between fixed and adaptive routing algorithms for circuit-switched networks are quite clear. It appears mandatory to have a failure adaptive routing algorithm

in a DOD environment. This provides an inherently more survivable network in the presence of link or node outages, jamming, or a more direct attack on network resources.

A.2.3 Routing Considerations in Packet-Switching Networks

Routing problems for packet-switched voice and data networks depend on whether the Fixed Path Protocol (FPP) or the Path Independent Protocol (PIP) is adopted for speech transportation. If the PIP is adopted, a single adaptive routing algorithm can be used for both voice and data and the considerations related to path length are not applicable. Note that other aspects of packet transportation may differ for voice and data packets, but these do not directly relate to the routing algorithm. For example, voice packets may have higher priority than data packets in some applications to minimize the variance of time gaps in the stream of speech packets.

If the FPP is used for voice packet transportation, then the path length considerations become important. However, in this case, degradation in network throughput is not as large as for circuit switching, since even if a long path is used for voice the inherent dynamic multiplexing of packet switching on communications links increases network utilization. Another factor limiting the path size in packet voice communications is voice intelligibility. Variance of time gaps in the packet speech stream of a particular conversation can be expected to be larger for longer path lengths and consequently intelligibility may decrease.

The method of minimizing path length in packet switching under FPP may be different than in the hybrid-switching technology. For example, one may have to maintain separate sets of values of delay estimates from a given node to other nodes—one set based on voice packets alone and the other based on data packets. The algorithm for fixed path setup may then take into account the impact on voice intelligibility resulting from a short, highly utilized path, or a longer path which is not heavily utilized.

The problem of routing for packet-switched voice and data must be further investigated with experimental testing of alternatives.

A.3 *CIRCUIT RESERVATION IN CIRCUIT-SWITCHING AND HYBRID-SWITCHING NETWORKS*

The notion "circuit reservation" is used to describe the process of end-to-end path identification followed by the actual seizure and dedication of capacity on that path for circuit-switched commmunications. The main problems here concern the time intervals between path identification, capacity dedication and the intervals during which the capacity is used. For example, if bidirectional capacity is dedicated to users link-by-link at the time of path identification (i.e., when a signaling message is propagated from source to destination), idle capacity results which is not effectively utilized until actual message transmission begins.

An objective of any circuit-switched network is to minimize the time interval between capacity dedication and transmission. This objective is significant under the fast circuit-switching technology because the rate of circuit establishment and disconnection is high when circuit switching every message of interactive data applications. However, this objective becomes even more significant in hybrid-switched networks where link capacities are dynamically shared between the packet and circuit-switched traffic classes because the stored packets can promptly utilize this capacity. Furthermore, the capacity wasted during the circuit reservation procedure increases for links with high propagation time, such as satellite channels, and for reservation of wideband circuits.

The circuit reservation problem creates a fundamental throughput-delay tradeoff in network design. If capacity is seized simultaneously with path identification, the time between connection request and end-to-end circuit availability is minimized but wasted capacity is maximized. Possible procedures for circuit reservation are briefly described below and their merits indicated [GTE, 1975].

Forward Allocation:

> This procedure dedicates two-way capacity while identifying the path from source to destination. Capacity dedication can coincide with signaling progress or use a "reserve and dedicate after time out" approach. The latter requires more complex node processing. The forward allocation scheme has low delay to "ring back" but inefficient capacity utilization. This strategy may result in dedication of capacity which is eventually released without being used if an end-to-end path cannot be established because of network congestion or a busy destination party.

Backward Allocation:

In this scheme path identification is done from source to destination, and bidirectional capacity is dedicated backwards from destination to source. Capacity dedication can coincide with the backward signaling or delayed as in the previous scheme. If the state of network load is changing rapidly, capacity may become unavailable when signaling backwards. This conflict can be resolved by making reservation when signaling forward and dedication when signaling backward using timeouts. However, complex node processing is then required. One implementation scheme for the latter approach is to introduce timeouts whereby switching nodes discard the reservation after the timeout. In contrast to the forward allocation scheme, the backward allocation scheme is characterized by higher delay to ring back but utilizes capacity more efficiently.

Forward and Backward Allocation:

This scheme is a combination of the two previous approaches. Capacity from destination to source is dedicated when routing forward from source to destination and capacity from source to destination is dedicated when signaling backward.

Other circuit reservation schemes are possible; for example, a source-destination protocol which allows reservations for future dedication may be used. In hybrid switching, future dedication can be performed using relative or absolute future frame indicators. These schemes are sensitive to signaling packet errors and retransmissions. Estimates in delay tables for packet routing can be utilized by these schemes. These allocation schemes may result in a large circuit setup delay but provide efficient channel utilization.

Not all the schemes described are equally applicable to circuit-switched and hybrid-switched networks. Schemes based on timeouts are mostly useful for hybrid switching, enabling packet transmission during the time interval between channel reservation and dedication. In traditional or fast circuit switching, such schemes are not useful. Another circuit reservation consideration is the possible reservation of a unidirectional circuit for file transfer applications.

Selection of circuit reservation strategies involve a tradeoff between switching and transmission cost since sophisticated reservation schemes result in efficient channel

utilization but require more complex node processing. Extensive study of these tradeoffs will be required to optimize use of network resources once the choice of switching strategy is made.

A.4 PROBLEM AREAS IN THE DESIGN OF HYBRID-SWITCHING NETWORKS

The design of hybrid-switching networks encompasses all elements of the design of circuit-switched and packet-switched networks. In addition, it includes the problem areas which stem from the dynamic sharing of resources by the two switching modes. Briefly stated, the problem of hybrid-switching network design requires the determination of minimum cost network resources (nodes, links, capacities) which satisfy average end-to-end delay for packet-switched traffic, average end-to-end loss probability for circuit-switched traffic, average end-to-end delay for circuit connection setup, and reliability constraints. Similar to circuit or packet-switched network design, it includes the subproblems of routing, capacity assignment, and topological design.

A methodology for hybrid-switched network design, computational techniques, and computer programs have been developed under this project [NETWORK ANALYSIS CORPORATION, 1977] . In what follows, several issues underlying network design and the areas in which they differ from the design of circuit or packet-switched networks are discussed.

The traffic requirements offered to the hybrid network include the circuit-switched load and average packet rate for each node pair. Based on the routing algorithms for circuit switching and the circuit-switched call origination rate, the pairwise signaling traffic requirements are derived. Consequently, the link flow includes circuit flow, packet flow, and signaling flow. The signaling traffic can be accommodated on dedicated slots in the frame or share capacity with regular packet-switched traffic. Other traffic parameters include voice digitization rates, packet sizes (regular and signaling), packet and frame overheads, and routing overheads associated with updating routing tables, and a precedence-priority structure.

The routing and capacity assignment procedures in hybrid-switched network design are stated below. When iteratively applied they obtain optimum flow and link capacities for a given network topology.

Routing:

Determine circuit-switching flows and packet-switching flows which minimize end-to-end loss probability for circuit-switched traffic and average end-to-end packet delay for packet-switched traffic given link capacities and other variables.

Capacity Assignment:

Determine the set of link capacities and frame boundaries which minimize total cost, satisfying end-to-end loss probability and average end-to-end packet delay, given flows and other parameters.

A.5 PERFORMANCE MEASURES IN PACKET VOICE NETWORKS

Several unique aspects of packet-switched network operation impose different performance measures for the transmission of digitized voice than those normally associated with data transmission.

A.5.1 Delay

The total time separating the instant when a sound is uttered by the talker until it is perceived by the listener (referred to as the system delay) consists of the following components:

- Local access delay (if any).
- Analysis (time to create a digitized representation of a speech time window).
- Packetization (time to accumulate a sufficient number of windows to form a packet to be transmitted).
- Backbone network delay (processing, propagation, queueing, transmission).
- Reassembly (if required).
- Buffer delay (for smoothing the packet speech stream).
- Synthesis (time to construct a synthetic version of the digitized speech).

Both the analysis and synthesis delays are properties of the voice digitization device used and are generally small. Both the packetization and reassembly delays are functions of the source-destination protocols employed. The destination buffer delay is only encountered by the first window in a sequence of windows which form a continuous segment of speech. Finally, the local access and backbone delays are also a function of the routing strategy, queueing and transmission at successive links in an end-to-end path, signal propagation, and tandem switch processing.

Empirical tests conducted by Bell Laboratories have demonstrated that if a fixed path delay in excess of 600 msec is inserted at the beginning of speech segments, most subscribers report difficulty in conversational interaction. Delays of 300 msec were unperceptable whereas delays of one second or greater were universally intolerable. Consequently, the total packet voice system delay (comprised of the previously outlined parts) should be held to well below 600 msec and ideally below 300 msec.

A.5.2 Speech Continuity

Interruptions in reconstructed speech can render most conversations unintelligible. Depending on the amount of speech contained in each time window, the listener can tolerate a certain duration of speech interruption. In essence, the listener can "bridge" gaps between consecutive segments. If the duration of these gaps exceeds this perceptual bridging interval, the speech will become "dropper" and ultimately unintelligible. Destination buffer control and the insertion of artificial delay can be used in order to preserve speech continuity. The lack of interruptions in synthesized speech can yield performance comparable to that obtained by transmission in a circuit-switched network. Simulation results on packet speech continuity and implications on speech quality are reported in [LINCOLN LABS, 1976].

A.5.3 Packet Error and Loss

The impact of errors in the digitized voice bit stream depend on the digitization technique employed. Although the waveform-based techniques such as PCM (Pulse Code Modulation), CVSD (Continuously Variable Slope Delta Modulation), etc. are relatively robust with respect to errors, errors in the synthesized voice obtained from lower bit rate techniques such as LPC (Linear Predictive Coding) and APC (Adaptive Predictive Coding) may lead to unintelligible speech. Furthermore, certain crucial parameters such as the pitch which are received in error can render speech unintelligible. Because of the stringent delay requirements, standard link level protocol procedures such as automatic retransmission may not lead to acceptable performance and consequently, forward error correction may have to be employed for selective speech parameters. End-to-end retransmission of voice packets is unacceptable. A second area in which errors could degrade performance would be if a packet header is corrupted by noise. In this event, the absence of any error control would

result in an altered address and the packet being subsequently misrouted or lost by the network. The lost packets pose another problem for the destination receiver because of the introduction of excessive packet gaps. The presence of misrouted packets in a conversation would be perceived as breaks in the continuity of the synthesized speech and again could seriously degrade performance. Although a certain incidence of the above phenomena could be tolerated, some forward error correction of headers is likely to be required. Error control may not be critical when the transmission environment is appropriately engineered. Packet loss from the misrouting and/or excessive network delay poses an obvious impediment to the listener's understanding of speech reconstructed at the destination. Protocol options such as waiting for late packets versus insertion of previous windows should be evaluated. The superiority of one technique over the other is not clear. Loss of windows may be of acute concern to the destination vocoder's operation in the event Variable Frame Rate (VFR) devices are employed. VFR devices do not transmit all speech parameters every window period. Only those parameters which have changed relative to a certain threshold since the last window period are transmitted. Using these techniques, the information contained in successive windows is no longer context-free. By means of an interpolative mechanism, the vocoder uses the information contained in the current window as well as previous windows in order to synthesize a segment of speech. Therefore, the loss of a previous window can prohibit the vocoder from accurately reconstructing the speech represented by the current window. Consequently, packet loss is of even greater concern in an environment which employs VFR devices. Another factor which may degrade packet voice network performance is background noise. If energy measurements are used to detect the presence of speech, when the noise reaches an energy level comparable to voice signals, the noise will be encoded and transmitted [LINCOLN LABS, 1976]. Robust silence detection techniques can be devised to overcome this problem [NEMETH, 1976]; however, this may prove expensive and be used only for selected subscribers.

A.6 PROTOCOL RELATED ISSUES IN PACKET VOICE/DATA NETWORKS

A.6.1 Connection Management

The problems of connection management will be encountered at the highest level of the network protocol and include access control, flow control, subscriber notification, and routing. A central issue concerns whether "connections" should in fact be managed at all (on a logical circuit basis) or should packets from all subscribers be allowed access with the flow control mechanism "balancing" load.

A.6.2 Access Control

Access control determines whether a subscriber requesting placement of a call should be permitted access to the network. Blocking, the standard mechanism employed in circuit-switched networks, can clearly be used for packet voice. Alternatively, more sophisticated techniques can monitor resource utilization and based on a specified algorithm decide whether to allow a conversation to proceed. Clearly, some form of subscriber notification (e.g., ringing, busy tone, etc.) must also be employed for human engineering considerations.

A.6.3 Flow Control

Once a conversation is established, packet voice flow can commence. However, flow control mechanisms must exist to ensure that network resources (e.g., channels, buffers, etc.) do not become overutilized. A number of techniques are possible. These vary in sophistication and the level of hardware-software interaction and include the throttling of packets via deletion, breakdown of certain conversations, and adaptive rate control between the vocoders and switch. The latter technique is reminiscent of the adaptive encoding schemes previously discussed and would require a somewhat more sophisticated vocoder-switch interface.

A.6.4 Packetization Options

A.6.4.1 Packet Length Options

The choice of packet length is an important parameter in any store-and-forward communications system. It is, however, significantly more complex in the context of packet

voice. The time to create a packet at the source switch can be excessive if the packet is long when low bit rate voice digitization devices are employed. Thus motivation exists for extremely short packets to minimize the packetization delay. Short packet length will also reduce the network queueing and transmission delay. On the other hand, if the network transport protocol requires the use of a large header (for routing, error control, internetworking, priority, etc.), the overhead which will exist when a small information packet size is used will be prohibitively high, thereby eliminating the economic advantage of voice packet switching. Hence, motivation exists for using long packets to reduce network overhead at the expense of increased packetization delay. In addition, long packets will reduce processing load on the switch.

Packet release rules may be oriented toward the creation of full packets (i.e., when a packet is "full" it is allowed to be transmitted), toward scheduling requirements (e.g., after 400 ms, the packet is released), or a combined approach. Full packets result in maximal efficiency, whereas schedule techniques bound the packetization delay.

A.6.4.2 Compound Packet Protocol Option

An obvious drawback associated with long packets is the delay required to collect windows from a single vocoder at low digitization rates. This can be circumvented if windows from different speakers are combined into the same packet since the creation of windows in different handsets is performed concurrently rather than consecutively. Such an approach would keep the packetization period small yet restrict the network overhead to a tolerable level by the use of long packets. Some increase in the header size is obviously necessary to identify windows with a particular conversation. Several protocol-related options also exist concerning the number and type of conversations which should be multiplexed and the source-destination savings within a single packet. Specifically, reduced packetization delay is encountered if arbitrary windows are placed in the same packet. However, packet splitting may be required at intermediate nodes in order to route windows to the appropriate destination. If conversation only between a specific pair of source-destination backbone nodes are multiplexed in the same packet, then no intermediate packet splitting is required and the amount of processing at tandem nodes is appreciably reduced.

A.6.5 *Traffic Management*

The presence of multiple packet traffic classes contained in the same network will necessitate some arbitration mechanism such as a priority system. For example, both the delay and continuity constraints for voice packets will in all likelihood be stronger than those associated with data and as such, voice packets should be given higher priority than data packets. Control and protocol-related traffic may possibly receive higher priority than voice. The existence of multiple vocoder types within the same system could require an implicit priority among voice packets. For instance, certain digitization techniques may be more tolerant of packet loss, errors, delay, etc. than others. Therefore, the associated error control, packetization option, etc. may be different for each type. Finally, processing requirements and buffer management within the switch may also have to be specifically tailored for individual traffic categories.

A.6.6 *Conferencing*

One of the advantages provided by packet switching of voice is the reduced bandwidth requirements for conferencing applications when compared to circuit switching. However, conferencing in a packet-switching network imposes some new problems because all parties cannot "hear" a speaker at precisely the same time as in circuit switching using conference bridges. Therefore, the protocol used to manage speaker and conference interaction plays an especially important role when packet voice is used. Conference protocols are presently being investigated as part of the speech compression research funded by ARPA. Further studies to determine the most efficient broadcast routing procedures for conferencing are also desirable.

ANDVT	Advanced Narrowband Digital Voice Terminal. A terminal development being sponsored by the Navy under the TRI-TAC Program.
APC	Adaptive Predictive Coding; a voice digitization technique.
AUTODIN	Automatic Digital Network. A DOD switched data network.
AUTOSEVOCOM	Automatic Secure Voice Communications System. A switched secure voice system of the DOD.
AUTOVON	Automatic Voice Network. A switched voice system of the DOD.
BLOCKING	Rejecting customer request for network access because of unavailability of network resources. Blocking is encountered in circuit-switched networks. *End-to-end blocking* is referred to as loss.
CCIS	Common Channel Interoffice Signaling. An advanced system for establishing and disconnecting circuits in a circuit-switched network.
CHANNEL	A path along which signal or data can be sent.
CIRCUIT	A two-way channel.
CIRCUIT SWITCHING	Switching as performed in the telephone network where a call is set up by establishing a circuit from one subscriber to another, the circuit being held for the duration of the call.
CROSS TALK	The unwanted transfer of energy from one circuit, called the disturbing circuit, to another circuit, called the disturbed circuit.

CONGESTION	Any communication network has a limit to the traffic it can carry. Beyond that limit the network must somehow restrict traffic. Congestion means the condition in which the network is overloaded.
CVSD	Continuously Variable Slope Delta Modulation. A voice digitization technique.
FLOW CONTROL	In store-and-forward communication networks, procedures for regulating traffic flow to prevent congestion.
FPP	Fixed Path Protocol. A protocol for transporting speech packets, whereby a fixed path must be followed.
HYBRID SWITCHING	A switching strategy providing both circuit-switching and packet-switching services.
LINK	A two-way communication path connecting two adjacent nodes or switching centers in a network.
LCP	Linear Predictive Coding. A voice digitization technique.
NODE	A switching center in the network or a junction of links.
PACKET	A block of data handled by a network in a well-defined format including a heading. A maximum size of packet is set and messages longer than that size must be carried as several packets.
PACKET-SWITCHING NETWORK	A network designed to transfer information in a store-and-forward mode in the form of packets. The packet and its format are internal to that network. The external interfaces may handle data in different formats.

PIP	Path Independent Protocol. A protocol for transporting speech packets, where packets need not follow one path.
PROTOCOL	A strict procedure required to initiate and maintain communication. Protocols may exist at many levels in one network such as link-by-link, end-to-end and subscriber-to-switch.
PCM	Pulse Code Modulation. A voice digitization technique.
ROUTING	The determination of the communications path by which a message or telephone call will reach its destination.
ROUTING, ALTERNATE	Determination of a secondary communications path to a destination when the primary path is unavailable.
ROUTING, ADAPTIVE	Routing in which the behavior adapts to network changes such as changes of traffic pattern or failures.
SIGNALING	In circuit-switching networks, the operation of identifying and establishing or disconnecting a circuit between source and destination subscribers.
SIGNALING MESSAGE	The message used for signaling.
STORE and FORWARD	The handling of messages or packets in a network by accepting the messages or packets completely into storage then sending them forward to the next center.
SYNCHRONOUS NETWORK	A network in which all the communication links are synchronized to a common clock.
TIME-DIVISION MULTIPLEXING	A multiplexing method in which the time on the multiplexed channel is allocated at different times to different constituent channels. The allocation may be repeated regularly (fixed cycle) or may be made according to demand (dynamic).

TIME OUT In a communication procedure, one party may have to take action if it gets no response from the other within a specified time. This occurrence (exceeding the allowed time) is called a timeout.

TASI Time Assignment Speech Interpolation. A technique of sharing a number of communication circuits by a larger number of speakers, by assigning circuits to active speakers and disconnecting speakers temporarily silent.

VDR Voice Digitization Rate. The bit rate of an active speaker.

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13. ABSTRACT

Alternative switching strategies for future integrated DOD voice and data networks are studied. Three fundamental problems are addressed: (1) The economics of integrating voice and data applications in a common communication system; (2) the comparison of alternative switching technologies for integrated voice and data networks; (3) the economics of low voice digitization rate devices.

Strategies examined are traditional, fast, and ideal circuit switching, hybrid (circuit-packet) switching, and packet switching. These strategies are examined in conjunction with a data base representing future Defense Department voice and data requirements. The major conclusion is that packet switching is substantially more cost-effective for serving these voice or data requirements than the other alternatives examined. The sensitivity of the results are tested with respect to traffic variations, cost trends of switching and transmission, and network performance variables. The significant variables which affect the conclusions are identified and quantified.

14. KEY WORDS

packet, circuit, hybrid, switching, voice networks, data networks, communication networks, integrated networks, vocoders, voice digitizers

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